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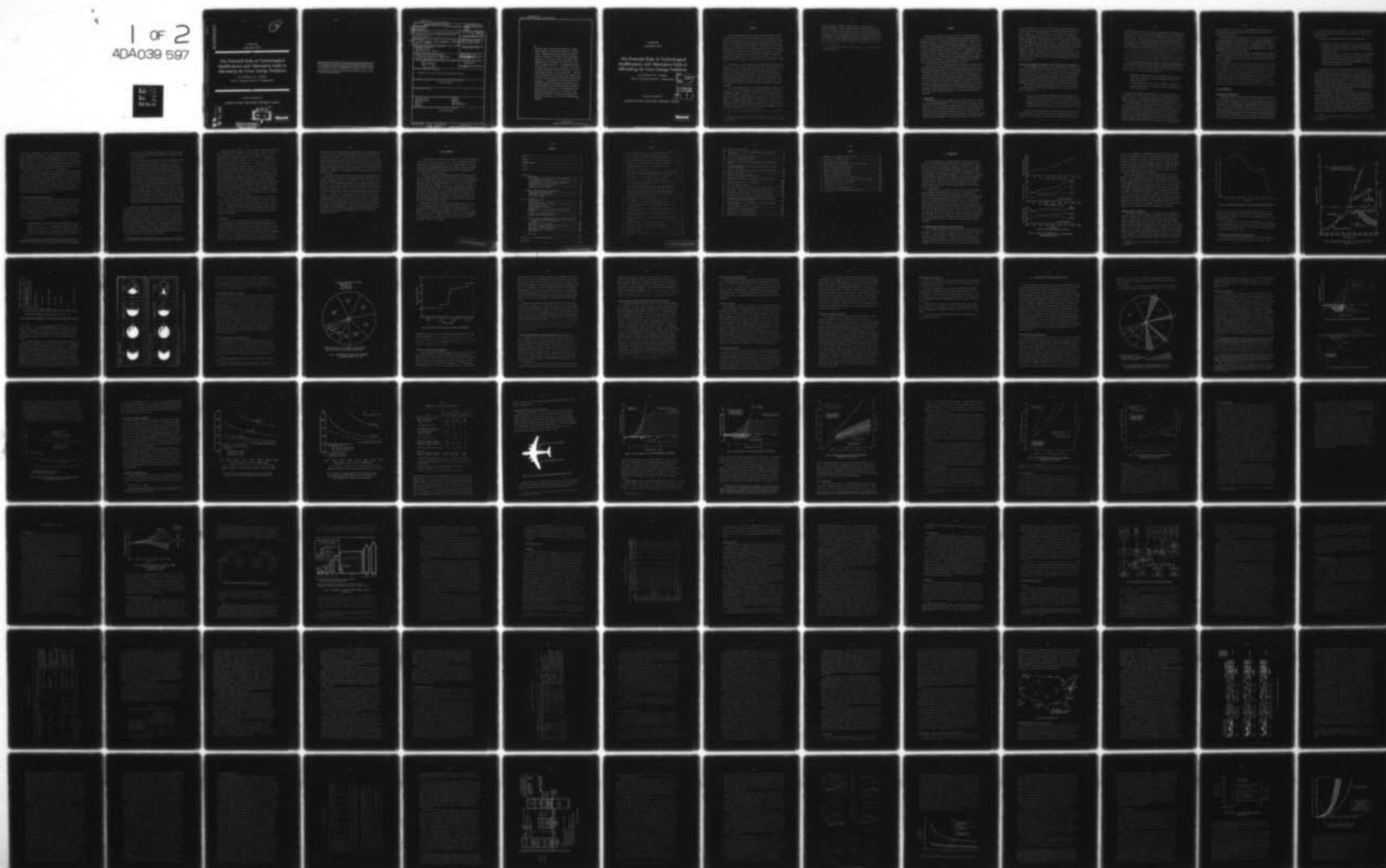

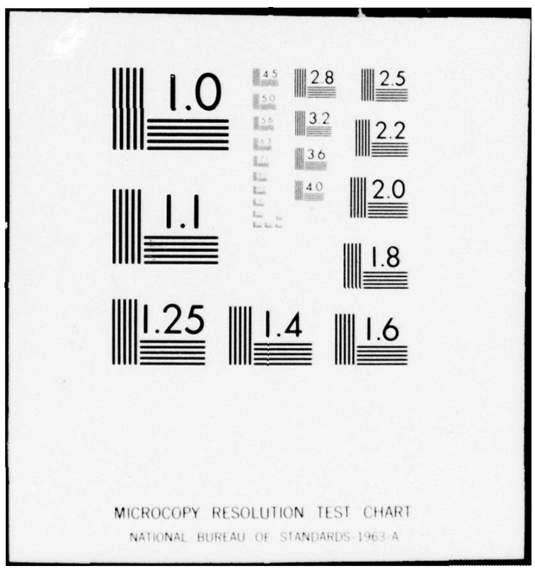
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The Potential Role of Technological Modifications and Alternative Fuels in Alleviating Air Force Energy Problems

J. R. Gebman, W. L. Stanley
with J. P. Weyant and W. T. Mikolowsky

A report prepared for

UNITED STATES AIR FORCE PROJECT RAND

Rand
SANTA MONICA, CA. 90406

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Examines short- and long-term measures to reduce the consumption of petroleum jet fuels by the Air Force. Engine retrofits and aerodynamic modifications to existing aircraft can save significant quantities of jet fuel; however, savings in fuel expenditures are not enough to offset high initial costs of engine retrofits. If accomplished early in an aircraft's life cycle, relatively lower costs of modest aerodynamic modifications may be recoverable through savings in fuel expenditures. Synthetic JP fuels derived from oil shale or coal appear to be the most attractive future alternatives to petroleum jet fuels. If the foreign oil cartel maintains its price-setting effectiveness and a synthetic fuels industry develops in the United States, development of an Air Force capability to interchangeably use fuels derived from crude oil, oil shale, or coal could be economically attractive and enhance the Air Force's position in the jet fuel marketplace. (Author)

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PREFACE

The fast-changing world energy situation could significantly influence the nature of future international conflicts and the effectiveness with which the United States Air Force could execute its missions. The "energy issue" has assumed a prominent position in both short- and long-term Air Force planning. Uncertainties in the future availability and economics of crude-oil-based jet fuels pose a particular challenge to the Air Force, the largest DoD consumer of jet fuel. To meet this challenge, the Air Force will be obliged to undertake measures to conserve jet fuel in the short term and to develop a future capability for using jet fuels derived from alternatives to crude oil.

In response to a joint request by the former Vice Chief of Staff (General R. H. Ellis), the Project RAND Air Force Advisory Group, and the former Air Force Chief Scientist (Dr. Michael Yarymovych) in his capacity as chairman of the Air Force Energy R&D Steering Group, a research effort was mounted at Rand for the purpose of identifying R&D activities that might provide (1) a short-term reduction in the Air Force's consumption of crude-oil-based jet fuels and (2) a long-term noncrude-oil-based fuel option for future aircraft development programs.

This report assesses the cost recovery potential and energy efficiency of selected technological modifications (engine retrofits and aerodynamic changes) to existing aircraft in the Air Force fleet to reduce present fuel consumption. For the long term, an assessment is made of (1) domestic energy resource alternatives to crude oil that might be suitable for the production of jet fuels, (2) the most desirable fuel forms derivable from those resources, and (3) the technological prospects and benefits of developing the capability to produce these fuels for use in Air Force engines.

This report and a companion report* that examines the military

*William T. Mikolowsky and Larry W. Noggle, *An Evaluation of Very Large Airplanes and Alternative Fuels*, The Rand Corporation, R-1889-AF, December 1976.

utility of large airplanes using alternative fuels constitute a unified treatment of Rand's energy research activities for the Air Force. This report should be useful to the Air Force Aero-Propulsion Laboratory, the Air Force Systems Command, and such Air Staff offices as DCS/Research and Development, particularly AF/RDQPN, which served as the Office of Primary Responsibility for this research. The work was performed under the Project RAND project entitled *Technology Applications Research*.

J. P. Weyant, a contributor to this report, is a consultant to The Rand Corporation.

SUMMARY

Crude oil has been the only fuel source for aircraft propulsion to date because it has been in abundant supply, has been relatively inexpensive, and has very attractive physical properties. However, over the next 50 years, the present geopolitical imbalance of crude-oil resources will be exacerbated by the continued depletion of oil reserves. As these supplies diminish, prices will escalate and availability will become less certain both at home and abroad. As a consequence, the Air Force will need to consider ways to reduce its consumption of crude-oil-based jet fuels in existing and in new equipment and might possibly have to develop propulsion systems capable of operating on jet fuels derived from energy resource alternatives to crude oil.

Since the Air Force is already working vigorously to modify peacetime operations to conserve energy in the short term, as well as examining the long-term prospects for new fuel-conservative aircraft designs, this report's primary focus is on two technological options that have received less attention thus far and that could reduce consumption of crude-oil-based jet fuels. Within this framework, the overall objective of this report is to identify and assess the possible benefits of R&D programs that might provide (1) a short-term reduction in Air Force jet fuel consumption through selected aerodynamic and propulsion modifications to the existing fleet and (2) a long-term noncrude-oil-based fuel option that could be exercised in future aircraft development programs.

A PERSPECTIVE

The world supply of recoverable fossil energy resources is limited and not uniformly distributed. In the case of crude oil, nearly three-quarters of the measured and indicated reserves are in the Middle East, North Africa, the Soviet Union, and Eastern Europe. United States production of crude oil has been declining in recent years and at the present time over 40 percent of the crude oil that we consume is imported. Even with full development of oil from the Alaskan north slope and the

outer continental shelf, and the use of enhanced recovery techniques, the Energy Research and Development Administration (ERDA) indicates that, at best, U.S. domestic crude-oil production might remain at today's levels between now and the end of the century. Nevertheless, domestic demands for liquid fuels are expected to increase significantly, even with aggressive conservation efforts. A continuation of the present trend of closing the gap between supply and demand by importing increasing quantities of crude oil might potentially threaten the policy independence, national security, and economic health of this nation. As a consumer of energy, a developer of technology, and a protector of the national interest, there are several short- and long-term options open to the Air Force that could reduce its future consumption of crude-oil-based jet fuels.

SHORT-TERM TECHNOLOGICAL MODIFICATIONS TO REDUCE JET FUEL CONSUMPTION

We have examined the cost and energy consequences of selected propulsion and aerodynamic modifications that might reduce the fuel consumption of the Air Force fleet. The cost recovery potential is measured in an energy context by comparing the savings in jet fuel expenditures with the cost of performing the modification. Energy efficiency is measured by comparing the savings in jet fuel energy with the energy required for manufacturing and installing fuel-conservation devices.

Analysis of the engine retrofitting option for the four leading jet fuel consumers of the Air Force fleet, the C-141, B-52, F-4, and KC-135, indicates that

1. Such an option could save considerable energy compared to the energy required to manufacture and install new engines, and
2. Even if jet fuel prices were to triple in constant dollar terms between now and the end of the century, savings in jet fuel expenditures would not be adequate to offset engine retrofit costs.

Most Air Force airplanes have engines developed in the late 1950s and early 1960s. Retrofit of newer, more efficient engines could result in a 20 to 30 percent reduction in fuel consumption, which would

more than offset the energy required to manufacture and install the engines. However, the reductions in expenditures for jet fuel would not be sufficient to recover the costs of the retrofit because of three major factors: (1) the high procurement costs for the new engines; (2) the low level of peacetime flying hours for military aircraft; and (3) the advanced age of the average aircraft by the time the retrofit program was completed (average fleet ages would be about 15 years or more).

These facts lead us to conclude that any proposal attempting to justify the cost effectiveness of the engine retrofitting option will have to consider not only reduced expenditures for jet fuel but also the possible operational advantages offered by enhancements in capability (e.g., greater range) or reductions in fleet size at equal capability.

We have also investigated the utility of modest aerodynamic changes that have been proposed for some transport-class Air Force aircraft--the C-141 and the C-130--to reduce drag and hence reduce fuel consumption. Analysis of this option indicates that

1. Aerodynamic modifications can save modest amounts of energy, even after considering the energy required to effect the modifications, and
2. If made early in the life cycle of an aircraft, savings in jet fuel expenditures can offset the costs of modest aerodynamic modifications.

Adding drag-reducing wing fillets to an unstretched C-141A and removing its vortex generators could reduce fuel consumption by as much as 8 percent. Our analysis indicates that such a modification could save more energy than that required for the modification.

In the late 1960s, such a modification was estimated to cost about $120,000 per aircraft (1974 dollars). At this price, savings in jet fuel expenditures would clearly offset the cost of the modification. If costs were to rise to $250,000 to $400,000 per aircraft (1974 dollars) to accomplish the modification, there is some doubt as to whether savings in fuel expenditures could offset modification costs before the fleet reached the end of its useful life. Nevertheless,

further exploration of the cost of an aerodynamic modification and a determination of the additional years the C-141A is to be kept in service seem desirable.

Modifications to the afterbody of the C-130 have also been proposed, to reduce aerodynamic drag an estimated 3 to 9 percent, depending on the extensiveness of the modifications. Such modifications would result in net savings in energy, but it is unlikely that costs could be recovered through savings in jet fuel expenditures because of the advanced age of most of the C-130 fleet.

The Air Force is currently testing the drag reduction potential of winglets using the KC-135 as a test bed. The cost and energy effectiveness of this modification will have to be assessed after the test program is concluded.

Prospects for reducing energy use by modifying aerodynamic characteristics and offsetting the modification costs through savings in jet fuel expenditures do not appear to be particularly attractive for aircraft currently in the fleet (with the possible exception of a C-141 modification). Nevertheless, the relatively lower cost of aerodynamic modifications compared to engine retrofits and the potential 5 to 10 percent reductions in fuel consumption lead us to conclude that the option may be viable for future aircraft if modifications are accomplished early enough in the aircraft life cycle to allow cost recovery.

FUEL ALTERNATIVES

Assessment of Alternatives

The recent three year time period during which large increases in jet fuel prices have occurred stands in stark contrast to the 25 to 50 year time period spanning basic research through operational usage that is typical of the development and implementation of new propulsion concepts. The Air Force, therefore, must be acutely attuned today to the possibility that in the future it may have to resort to an alternative fuel that may require either the modification of existing engine hardware or even the introduction of a new generation of aircraft engines. Our initial research on alternative fuels sought to identify the most

promising energy resource alternatives to crude oil that could be used for the production of new jet fuels and to determine the most attractive fuel forms.

Analysis of the alternative fuels option indicates that

1. Domestically abundant oil shale and coal are the most promising energy resource alternatives to crude oil that could be used for the production of future military jet fuels into the next century, and
2. A synthetic jet fuel, or synthetic JP, similar to conventional hydrocarbon jet fuels in use today, is the most attractive military fuel form derivable from U.S. oil shale or coal resources, given the energy conversion technology that is expected to be available in the future.

An analysis of the cost and energy efficiency of the production and distribution of jet fuels from coal revealed that a synthetic JP fuel would require lower energy expenditures and would result in a less costly fuel product than the other two major alternatives--the cryogenic fuels liquid hydrogen and liquid methane. Synthetic JP also has the advantage of being far more similar to jet fuels in use today than the two cryogenic alternatives, which should ease transitional problems for military users and promote its assimilation into a domestic fuels market now dominated by crude-oil-based fuels.

A related mission analysis of large transport-class airplanes (with gross weights of 1 to 2 million pounds) fueled by synthetic JP, liquid hydrogen, liquid methane, or nuclear propulsion has indicated that for a broad class of present and future mission applications, a synthetic-JP-fueled aircraft enjoys a significant advantage in terms of cost and energy effectiveness.* Nuclear propulsion begins to look attractive only for station-keeping missions that require large station radii (greater than 4000 n mi) and extremely long loiter times on

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*William T. Mikolowsky and Larry W. Noggle, *An Evaluation of Very Large Airplanes and Alternative Fuels*, The Rand Corporation, R-1889-AF, December 1976.

station (e.g., hundreds of hours). At present, no missions requiring such a capability are apparent. Analysis suggests that liquid-hydrogen-fueled military aircraft would become attractive only if there were dramatic reductions in the energy requirements and costs for liquefying gaseous hydrogen. Projections of possible advances in hydrogen liquefaction technology by liquid hydrogen manufacturers indicate that such dramatic improvements are not likely to be forthcoming.

Despite the attractive features of synthetic JP, there are definite resource, capacity, environmental, government policy, and international factors that could tend to limit its availability in the future. Nonetheless, our research results suggest that there is a strong likelihood that a coal and oil-shale synthetic fuels industry could develop in the United States between 1990 and 2025, and that the switch from crude-oil-based jet fuels to coal- or oil-shale-based fuels in this time period would be dictated by comparative economics rather than by a total lack of availability of crude oil.

Implications for Synthetic Jet Fuel R&D

The latter stages of our research on alternative fuels focused on: (1) the identification of R&D needed to develop the synthetic jet fuel option; (2) the delineation of conditions under which it may become necessary to change to fuel and/or engine technologies that are not totally dependent on crude oil as an energy source; and (3) an assessment of the possible benefits to the Air Force resulting from the development of a synthetic jet fuel propulsion capability.

Our findings indicate that

1. Significant R&D is needed to develop the synthetic jet fuel option for the future, at least part of which will probably have to be conducted by the Air Force to assure a suitable fuel product for military use. An aggressive program of basic research should probably begin now,* considering the 25 to 50

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*A limited amount of Air Force research in this general area is already being conducted by the Air Force Aero-Propulsion Laboratory and one of its contractors, the Exxon Research and Engineering Company.

year life cycle of propulsion technology, and considering the foreboding projections on the availability of domestic crude oil in the future.

2. The R&D should focus on developing a full understanding of the physical, chemical, and economic influences of synthetic jet fuels on refinery operations and on military jet engines.
3. Any characterization of possible economic benefit to the Air Force from possession of a multifuel capability is subject to great uncertainty, because of the influence that the foreign oil cartel may be able to exert on the energy conservation and supply options that are developed domestically in the future. If the foreign oil cartel's price-setting effectiveness does not diminish in the future, the 1980 present value benefit* to the Air Force between 1995 and 2020 of being able to procure the cheapest jet fuel alternative could amount to roughly $1 billion (1974 dollars). Conversely, if the cartel's price-setting effectiveness does diminish, which could delay the introduction of synthetic fuels in the United States, any economic benefit from possession of a multifuel capability would be so delayed that the 1980 present value benefit would be negligible.

The R&D activities outlined above should reveal the proper technology balance between emphasis on energy conversion (e.g., the refinery) and on energy use (e.g., the military jet engine). Success in these R&D activities alone, however, will not assure that the synthetic jet fuel option can be exercised in the future, since the R&D policies adopted by ERDA and by the private sector will in large part determine the future availability of technologies for producing synthetic crude oils suitable for refining to jet fuels. Furthermore, even if the technologies are developed, their possible commercialization will be heavily influenced by world oil prices, and particularly by the price-setting effectiveness of the foreign oil cartel.

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*The present value economic benefit is referenced to 1980 because that is when the major R&D expenditures would likely have to commence.

Since the economic benefit to the Air Force from possessing a multifuel capability is so sensitive to future trends in world oil prices, three alternative scenarios on the price of imported crude oil were considered in the benefit assessment. If the price of imported oil were to rise to $19.50 per barrel (1974 dollars) by the year 2000, the 1980 present value benefit of the multifuel capability between 1995 and 2020 could amount to roughly $1.9 billion (1974 dollars). The $1 billion benefit previously cited is assumed to result if the price of oil rises to $15 per barrel (1974 dollars) by the year 2000. If, however, the foreign oil cartel were to lose its price-setting effectiveness, resulting in an assumed year 2000 price of $9 per barrel (1974 dollars), any economic benefit stemming from a multifuel capability could be delayed, and hence, be negligible in 1980 present value terms, since the direct economic stimulus for the development of a synthetic fuels industry would be delayed. However, in this circumstance, the United States could find itself in the undesirable situation of having to import 90 percent of its crude oil by 2020, with all the attendant national security and economic problems.

If the foreign oil cartel continues strong, and if a synthetic fuels industry is developed in the United States, a policy of relying solely on crude oil for jet fuel needs could place the Air Force in, at best, an awkward marketplace negotiating posture by the turn of the century. Furthermore, by the time other energy users begin shifting to coal and shale oil, crude oil in the low extraction cost category will have been depleted.

CONCLUSIONS

Analysis of short-term and long-term Air Force options for reducing consumption of crude-oil-based jet fuel has indicated that an aerodynamic modification for the C-141 may still be an attractive fuel-conserving modification, depending on the additional number of years the C-141 force is to be kept in service and the cost of the aerodynamic modification. Some additional exploration of both these questions appears warranted. Technological modification of other aircraft in the present Air Force inventory does not seem to be warranted in view of

the cost and the limited potential returns that are in large part driven by the low annual utilization rate for military aircraft and the advanced age of the fleet. It seems that the only major way that technology can potentially contribute to reductions in Air Force consumption of crude-oil-based jet fuels in a cost-effective manner is through force modernization, by the introduction of aircraft with improved fuel consumption characteristics, or by development of a synthetic jet fuel propulsion capability. The research in this report has focused on the latter option.

If an aggressive synthetic fuels commercialization program is not instituted prior to the end of the present century, the United States could be importing nearly all of the crude oil that it consumes by the year 2020. With an aggressive synthetic fuels commercialization program, the Air Force may be able to realize a significant cost avoidance in terms of reduced fuel costs, if it is in a position to use a jet fuel that is derived from a coal- or oil-shale-based replacement for crude oil. However, to be in a position to use such a synthetically derived jet fuel, the Air Force may have to initiate a more substantial R&D program before the end of this decade in order to develop the basic fuel and engine technology that could then be used in military jet engines that are designed in the late 1980s and early 1990s. An investment in this R&D should be considered as a hedge against uncertainties in the economics and availability of crude-oil-based jet fuels in the future.

ACKNOWLEDGMENTS

The authors wish to express their thanks to Dr. Michael Yarymovych, former Chief Scientist of the Air Force, for his guidance during the formative stages of this research. W. B. Graham, manager of the General Purpose Forces/Engineering Technology Program at Rand, provided invaluable assistance in critiquing the various briefings prepared during the course of the research.

A number of persons at the National Aeronautics and Space Administration Langley Research Center, the Defense Energy Information Service, the Defense Fuel Supply Center, and the Air Force Aero-Propulsion Laboratory provided timely information on the subjects of synthetic fuels and DoD fuel consumption and costs. In particular, we wish to acknowledge Robert Witcofski of the NASA Langley Research Center, who kept the authors abreast of on-going liquid hydrogen studies being performed by and for NASA. Analysts from the Sun Oil Company, the Exxon Research and Engineering Company, and the Applied Systems Corporation discussed with the authors the results of their research on coal- and oil-shale-based jet fuels.

Rand Graduate Institute student Richard Fallon assisted in the task of preparing inputs and interpreting the outputs of the U.S. energy system model used in the research. Rand staff members C. C. Mow and W. D. Gosch supplied breakdowns of Air Force jet fuel consumption by aircraft type. Finally, we wish to thank Rand staff members J. S. Kakalik and J. R. Nelson for their careful and constructive reviews of a draft of this report.

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I. INTRODUCTION

The fast-changing world energy situation will influence both the nature of future international conflicts and the effectiveness with which the Air Force can execute its mission. Therefore, the "energy issue" will become an increasingly significant factor in long-range planning, both in the setting of future mission requirements and in the development of corresponding hardware. In the short term, however, existing hardware might have to be modified to suit evolving mission requirements while coping with the various facets of the Air Force's "energy problem." Over the long term, technology and alternative energy sources will have to be more fully exploited to meet future mission requirements.

An examination of technological alternatives for easing and perhaps ultimately eliminating the Air Force's total dependence on crude-oil-based fuels for aircraft propulsion essentially defines the scope of the analysis contained in this report. Our overall objective has been to identify and assess the possible benefits from R&D programs that might provide (1) a short-term reduction in Air Force jet fuel consumption through selected aerodynamic and propulsion modifications to the existing fleet, and (2) a long-term option to use noncrude-oil-based jet fuel in future aircraft. This introductory section lays the groundwork for this assessment by putting Air Force energy consumption into perspective and by identifying some of the major problems confronting the Air Force as a result of the evolving world energy situation.

THE COMPOSITION AND GROWTH OF ENERGY CONSUMPTION

In our modern industrialized society, energy consumption has been growing at a very rapid rate. Figure 1 shows the growth and composition of U.S. energy resource consumption since World War II. Note that during the last decade U.S. energy consumption increased at a 3 percent compound growth rate, which implies a doubling of energy consumption every 23 years (Fig. 1a). Clearly, the major growth has

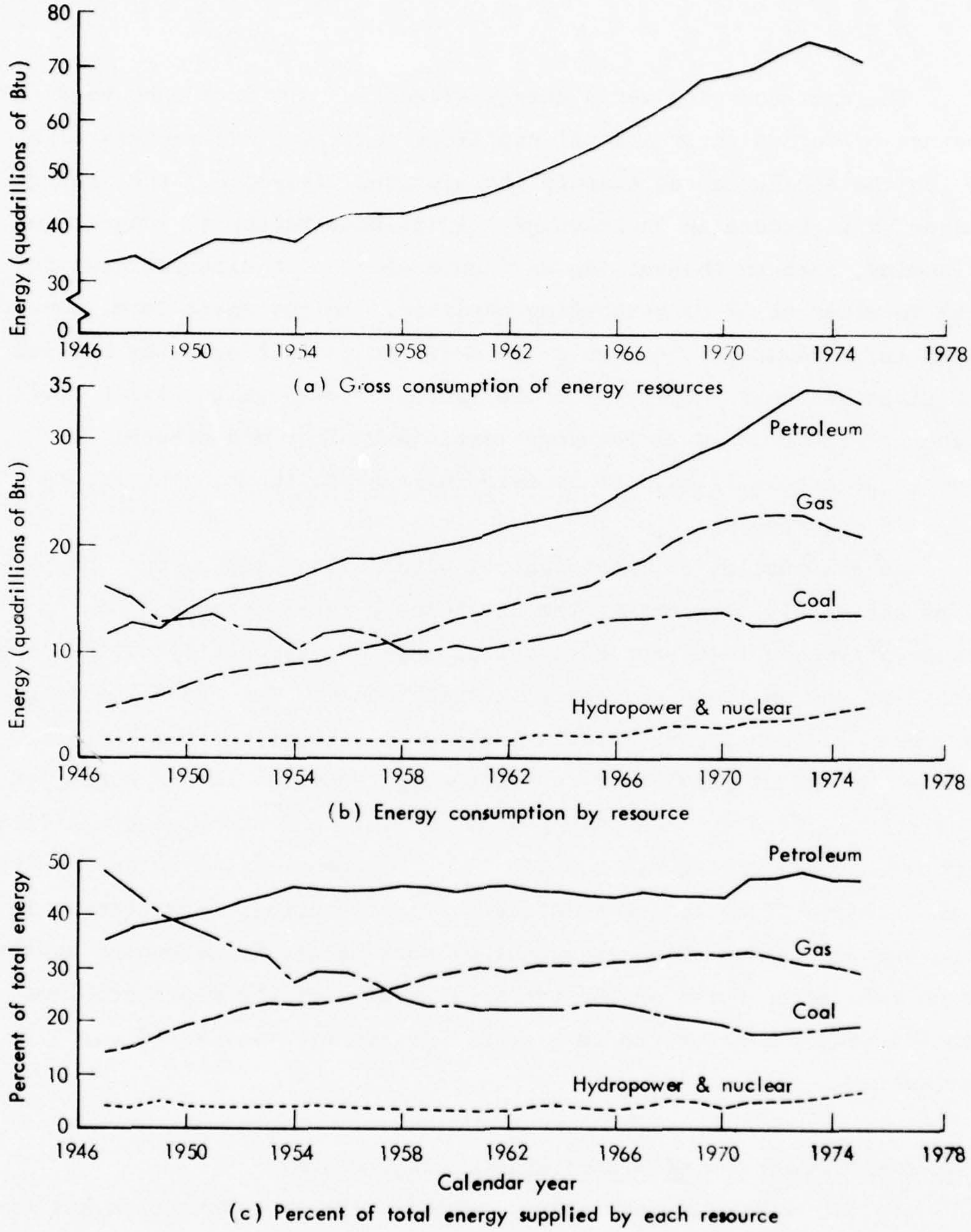

Fig. 1 — Level and composition of U.S. energy resource consumption (from Ref. 1)

been in the consumption of petroleum and natural gas (Figs. 1b and 1c). This is not surprising, since in the past these resources were among the most economical, efficient, and transportable. The latter two attributes certainly still hold; however, the recent explosive growth in crude-oil prices, and the anticipated growth in natural gas prices, are forcing the United States and other nations to consider a wide range of alternative courses of action to counter the rising prices of these two traditional energy resources.

World energy demands have been increasing by about 5.5 percent per year, an even greater rate than that experienced in the United States. Some estimates indicate that by 1990 Western Europe's petroleum consumption may equal that of the United States, with Japan consuming about two-thirds to three-quarters that of the United States.[(2)] It is highly doubtful that the current rate of increase in the demand for energy can be sustained indefinitely. Increasing energy prices, scarcities, and uneven distribution of energy resources, environmental concerns, and lack of capital to support current growth rates will probably tend to temper growth in demand. While Air Force petroleum consumption has been declining in the post-Vietnam time period (see Fig. 2), the Air Force, as a consumer of energy, will be competing with other users in the marketplace for the same scarce resources.

FUTURE SUPPLIES OF CRUDE OIL

The crude-oil supply situation is characterized by diminishing domestic production and an uneven distribution of world crude-oil resources. Projections by the Energy Research and Development Administration (ERDA) indicate that, at best, crude-oil production might remain constant between now and the end of the century (Fig. 3). Moreover, unless new sources of liquid fuels are developed and conservation measures are successful, growing demands for liquid fuels will probably result in even greater dependence on crude-oil imports.* Such a trend could threaten U.S. economic health, policy independence, and security because of North African and Middle Eastern oil-exporting countries'

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*During 1976 the United States imported over 40 percent of its petroleum.

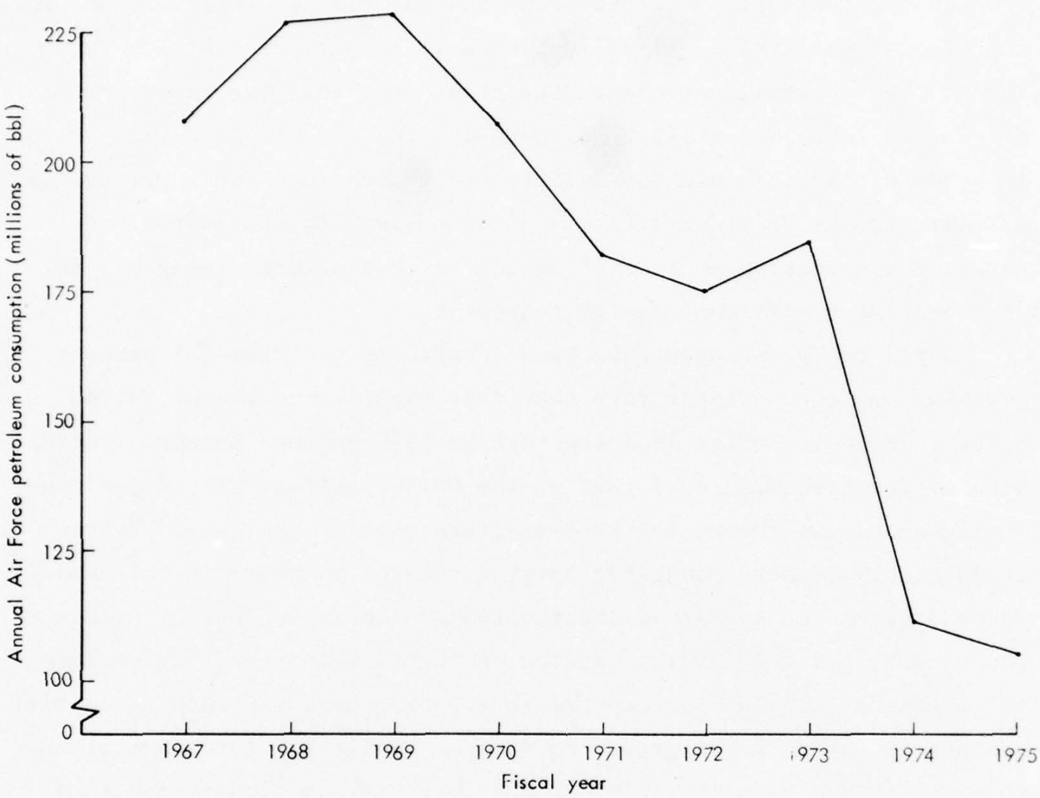


Fig. 2—Annual Air Force petroleum consumption worldwide (from Ref. 3)

control of much of the world's proven oil reserves (Fig. 4). The situation is particularly foreboding for our allies, since Western Europe imports 98 percent of its oil, and Japan imports virtually 100 percent of its oil.(2)

The discussion thus far has centered primarily on U.S. energy supply and demand as a whole. Next we focus on the energy consumption of the Air Force compared to that of the Department of Defense (DoD), the United States, and the world.

A PERSPECTIVE ON AIR FORCE ENERGY CONSUMPTION

The United States, with only about 6 percent of the world's population, consumes annually about one-third of the world's total

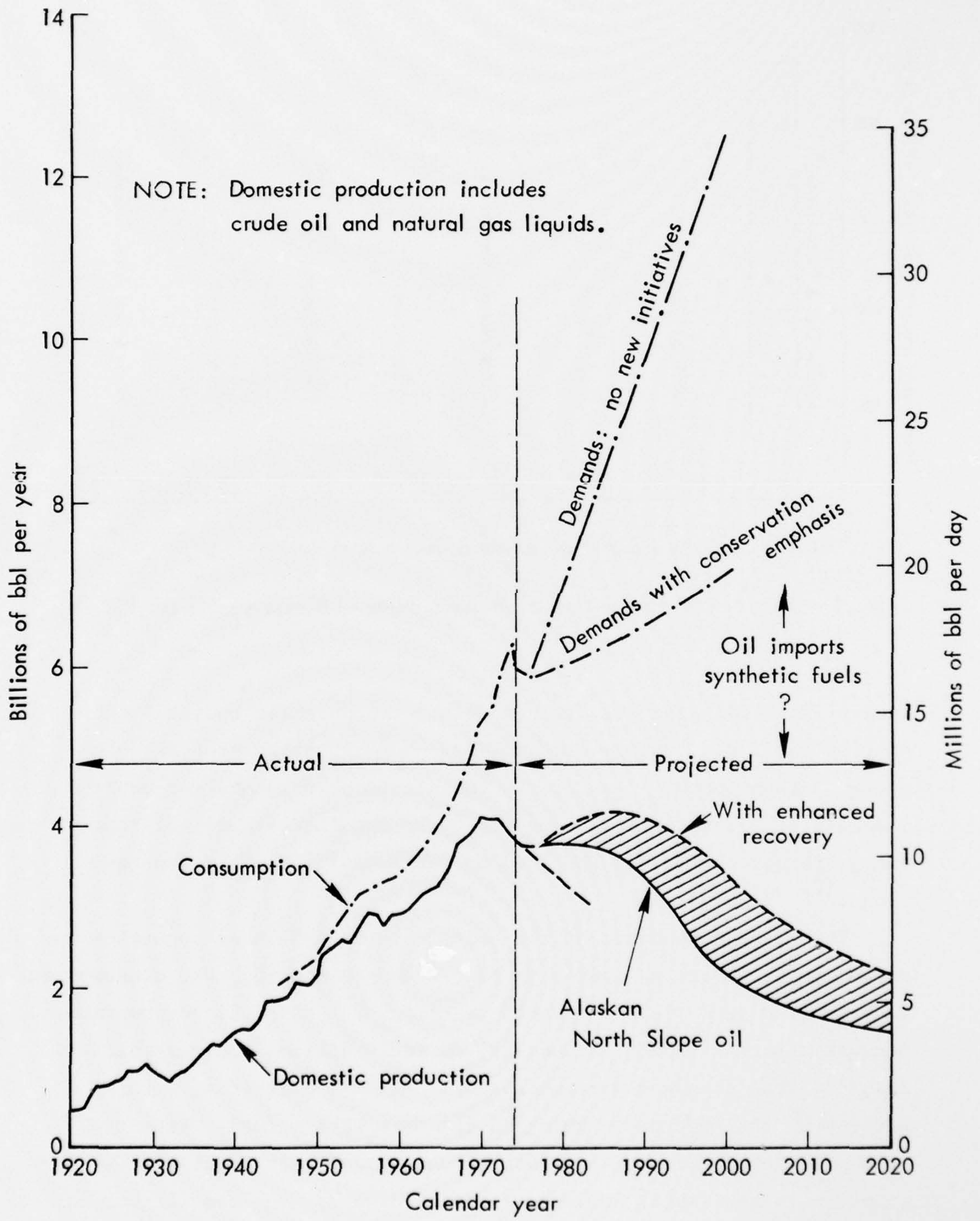
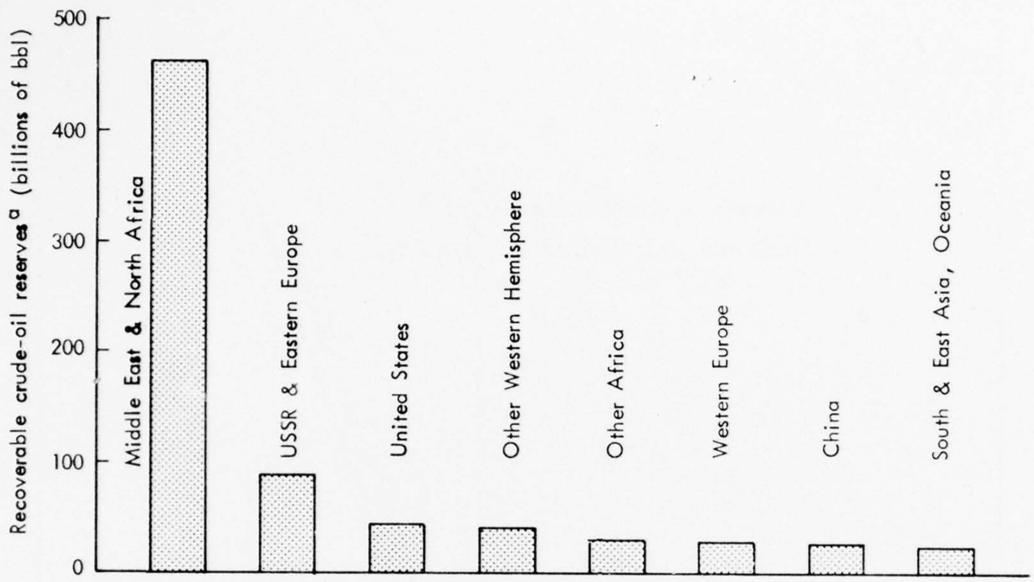


Fig. 3 — Projected domestic crude-oil production and demand (from Ref. 4)

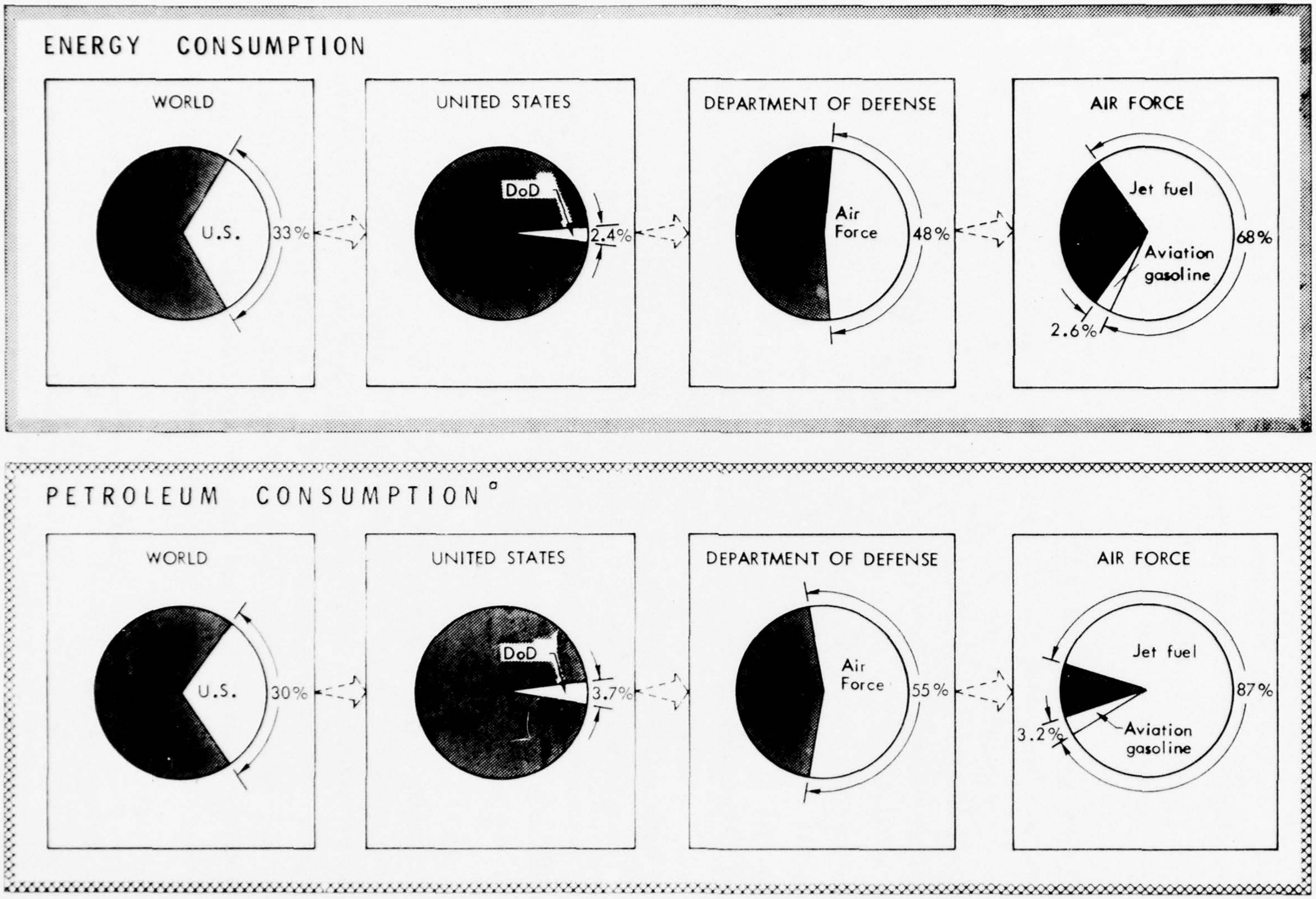


[a] Generally includes measured and indicated reserves as of January 1, 1975.

Fig. 4—Worldwide distribution of proven crude-oil reserves (from Ref. 4)

energy (Fig. 5). The DoD, in peacetime, accounts for only 2.4 percent of total U.S. energy consumption; however, because of the high energy intensiveness of aircraft, the Air Force accounts for nearly one-half of all DoD energy consumed, with about two-thirds of that energy being consumed in the form of jet fuel for aircraft operations.(2)

The heavy dependence of the United States and other countries on petroleum as an energy source is also shown in Fig. 5. DoD consumption of petroleum is a small but vital fraction of total U.S. consumption. Because aircraft depend exclusively on fuels derived from petroleum, the Air Force consumes over one-half of all DoD petroleum, with 87 percent of that petroleum being in the form of jet fuel. From the standpoint of total national energy consumption, Air Force energy consumption is not large; however, the Air Force and the rest of DoD do account for a large fraction of total U.S. demand for jet fuels. Specifically, military demand in the Continental United States for JP-4



[a] Petroleum accounts for about 43 percent of world energy use.

Fig. 5 — Perspective on peacetime Air Force energy consumption (from Ref. 2)

and JP-5 jet fuels is about 27 percent of total U.S. demand for jet fuels.[2] The largest consumers of jet fuel in the Air Force fleet are the transport and bomber aircraft (because of their large size and greater level of flying activity) and F-4 fighter aircraft (because of their greater numbers) (see Fig. 6).*

ENERGY PROBLEMS FOR THE AIR FORCE

We have noted that the United States and her NATO allies depend increasingly on energy imports, while the USSR is the only so-called developed country that produces more energy from its own resources than it consumes.[2] The energy-production deficiency of NATO countries presents serious problems to the alliance, its members, and the military establishments of its member countries. The problems range from providing energy to support allied military operations to preventing the disruption of the economies of the Free World. As evidenced by the "1973 Energy Crisis," such problems can be orchestrated to serve the political interest of the countries that export energy to the NATO allies. Furthermore, the 1973-74 oil price† escalation showed that in the process of serving their own economic interest, energy exporting nations could synergistically strengthen their political influence by imposing severe hardships on the economies of Free World countries.

Impact on the Budget of Rising Fuel Costs

One immediate impact of the world energy situation has been on the amount spent by the Air Force on energy, annually, three-quarters of which is devoted to jet fuel. Figure 7 shows the explosive growth in jet fuel (JP-4) prices in the last four years. Despite significant conservation efforts, the price that the Air Force pays for jet fuel has risen by over $1 billion during the last two years, such that

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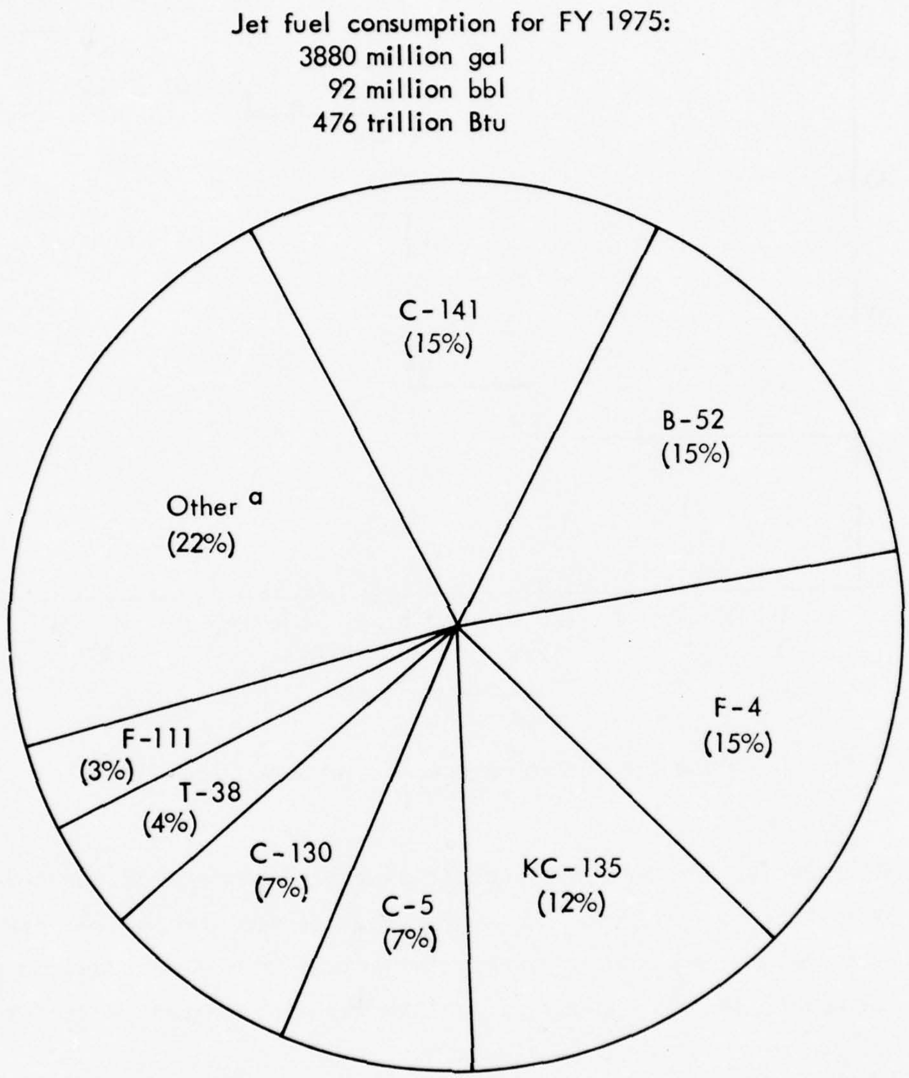
*Personal communication from Willian Vance, Defense Energy Information Service, October 1975.

†Over this period of time, the Organization of Petroleum Exporting Countries about quadrupled the price of their oil exports.



[a] Each aircraft type in this category accounts for less than 3% of total Air Force jet fuel consumption.

Fig. 6—Estimated Air Force jet fuel consumption by leading consumers, FY 1975

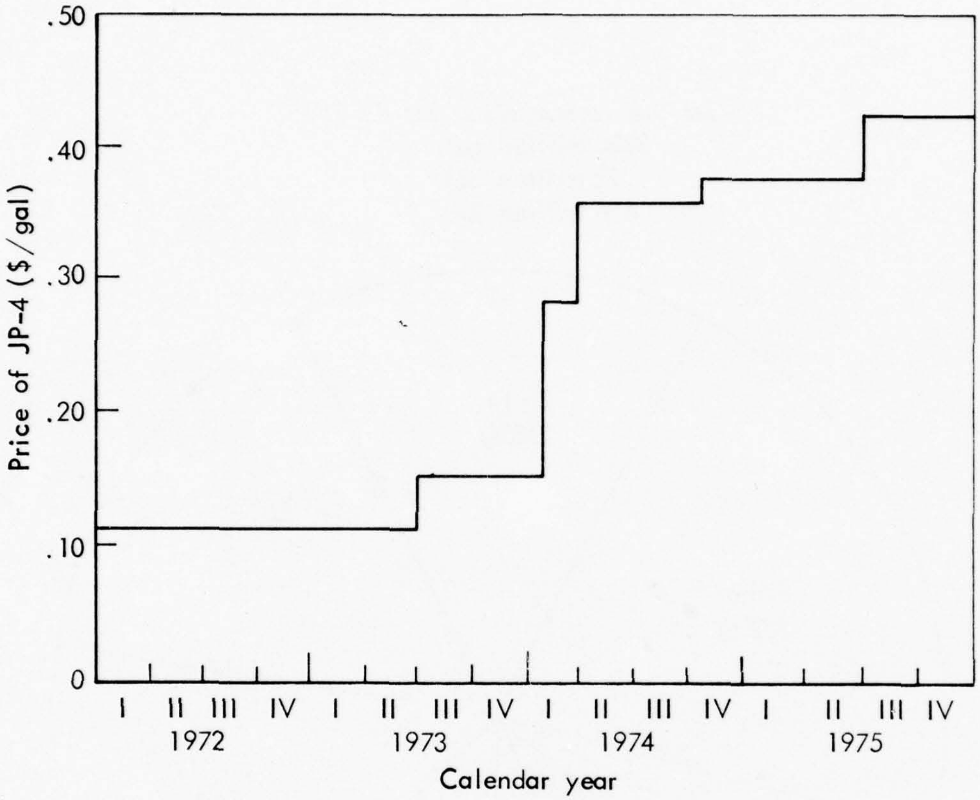


Fig. 7—Price the Air Force pays for jet fuel (from Ref. 6)

expenditures for jet fuel now constitute over 5 percent of the total Air Force budget.(5) *Thus, one energy-related problem for the Air Force is the growing cost of energy in general and of jet fuel in particular--costs that may usurp funds that might otherwise be used to develop and procure new weapon systems.*

Visibility of DoD Energy Consumption

A less quantifiable problem stems from the fact that the DoD and the Air Force are highly visible consumers of petroleum products. This visibility is not a result of the amount consumed by the military. (Indeed, we have already noted that the Air Force accounts for only about 2 percent of U.S. petroleum consumption.) The problem stems more from the manner in which the petroleum is used. When petroleum

supplies run low for the domestic sector, the government requests the public to turn down air conditioning, lower thermostats, drive at reduced speeds, and tolerate elevated prices for fuel. At such times, government consumption of energy becomes generally more visible to the public--in particular, military consumption of jet fuel is prone to become highly visible to the public during peacetime. Consequently, the public might expect the Air Force to cooperate in energy conservation, by procuring fewer airplanes and/or reducing peacetime operations to conserve fuel, resulting in a degradation in overall capability.

Reductions in peacetime flying hours influence the Air Force's war-fighting capability in at least two ways. First, there is degradation in pilot proficiency, unless some compensating action is initiated (such as the use of simulators). Second, if substantial reductions are instituted on a permanent peacetime basis, maintenance and supply systems might become "rusty" through reductions in maintenance manpower and spare parts inventories. *Thus, another energy-related problem for the Air Force is that the high visibility of peacetime jet fuel consumption may lead to reductions in war-fighting capability because of restrictions on peacetime operations and/or reductions in aircraft procurement.*

Loss of Overseas Bases or Overflight Rights for U.S. Airlift

The dependence of our NATO allies on oil imports is likely to spawn divergent national interests within the NATO alliance when it comes to dealing with international incidents involving the oil-producing nations. Even in incidents where there is consonancy of national interest within NATO, there may be a widespread reluctance among members to participate overtly. In either case, the U.S. Air Force cannot rely on either the overt cooperation of our allies or on the use of their air bases or their granting of overflight privileges during future conflicts involving the interests of the oil-exporting nations.

The total loss of overseas bases or overflight privileges could significantly reduce the effectiveness with which existing aircraft

could quickly deploy U.S. forces to distant parts of the world. It could also diminish U.S. ability to use airlift to offset the Soviet navy's growing capability to challenge sealift forces in some parts of the world. Past reductions in U.S. overseas forces have been predicated on an airlift capability, without which our effectiveness could be significantly degraded. *Thus, one of the significant energy-related problems for the Air Force is the potential loss of overseas bases or overflight privileges during an energy-related conflict.*

Time Required to Develop Alternative Propulsion Technologies

As crude-oil supplies decrease in the face of increasing demand, it is reasonable to expect that the price of crude-oil-based jet fuel will increase to the point where alternative fuel sources and/or propulsion technologies may become cost effective. The implementation of such alternatives, however, could involve many years of research and development and the need to procure entirely new fleets of aircraft. In this latter regard, it is of interest to note that over one-half of the Air Force jet fuel is consumed by aircraft that were initially designed some 20 years ago and are expected to remain in the fleet in significant numbers for another decade. This suggests a 20- to 30-year design replacement cycle. However, long before these aircraft could be replaced by a fleet using a non-oil-based fuel, a technology base would have to be developed and alternative aircraft designs examined. Depending upon the propulsion technology proposed, this could take from 10 to 20 years. Thus, the overall process of developing a new propulsion technology base, evaluating alternative designs and phasing in new aircraft could take from 30 to 50 years to complete. This time frame is commensurate with the time period during which some expect world annual crude-oil production to level off and start declining.[7] *Thus, a long-term energy-related problem for the Air Force is the lead time required to develop and apply alternative non-oil-based propulsion technologies.*

ENERGY ROLES FOR THE AIR FORCE

There are means by which the Air Force can cope at least in part with the aforementioned energy problems--by actions within its roles as a *consumer of energy*, a *provider of technology*, and a *protector of national interests*. However, Air Force actions alone cannot solve the energy problem. Solutions must be worked out at the national and international levels. The primary energy role for the Air Force will be to adapt itself to those solutions and to participate in their implementation.

Consumer of Energy

As a consumer of energy, the Air Force has already taken significant steps to reduce its energy consumption by curtailing nonessential peacetime operations. To further conserve jet fuel, the Air Force can also consider short-term technological options that might reduce the energy consumption of its fleet. An analysis of selected aerodynamic and propulsion options constitute the substance of Sec. II. For the long term, the Air Force can prepare to adapt to alternatives to crude oil in the future. As an energy consumer, the Air Force has a vital interest in when alternative fuels might become available and in the quantity, characteristics, and cost of the alternative fuels. Since national energy policy will influence the development of alternative fuel technologies, the Air Force must be aware of the impact that conversion to an alternative fuel would have on its ability to perform its mission and must seek to influence national energy policy decisions in a way that will make them compatible with Air Force requirements.

Provider of Technology

The Air Force has traditionally been a leader in the development of aircraft, missile, and munitions technology. As an experienced technology developer, the Air Force may play a role in developing the necessary technology for reducing reliance on crude-oil resources. In taking this role, the Air Force can contribute to the solution of the nation's long-term crude-oil-depletion problem, and, being an active technology developer, it can better anticipate and evaluate its own position with regard to alternative fuel-based technologies.

The Air Force could make key contributions in a number of technology areas. For example, the Air Force has long been a major sponsor of the research and development of advanced jet engine technology. This turbine engine technology has obvious applications for the civil sector as well (e.g., high-technology turbines for more efficient electric power generation). Further, the Air Force, through its Aero-Propulsion Laboratory, has much experience in evaluating the impact of fuel properties on the operation of turbine engines. This expertise should prove valuable as the nation begins to use new liquid fuels with properties different from those of petroleum fuels. Other Air Force technology efforts, although not specifically energy-motivated, may provide a valuable contribution to the long-term development of nuclear fusion reactors.

Protector of National Interests

As an instrument of U.S. foreign policy, the Air Force must respond to emergencies around the world on short notice (e.g., the airlift mission). In its role as a protector of the national interest, the Air Force must adjust its fleet capabilities to be responsive and effective in energy-related conflicts, including those situations in which it might be denied overseas base privileges or in which fuel availability becomes critical. One short-term approach to meeting the overseas base problem is to modify the existing fleet to increase the number of aircraft capable of being refueled in flight. Such a modification has already been incorporated on the C-5A. The C-141A fuselage stretch program incorporates an in-flight refueling receptacle to provide more operational flexibility. A longer-term option would be to develop new aircraft of greater size (e.g., gross weights of 1 to 2 million pounds) and range/endurance than those of today. Such aircraft may allow major enhancements in capability while significantly reducing fuel consumption. For example, a companion Rand analysis indicates that a fleet of transport aircraft in the 1 to 2 million pound gross weight class fueled by JP might use roughly 30 percent less energy when deployed in a NATO strategic airlift than a fleet of C-5-class aircraft.[8]

ORGANIZATION OF THE REPORT

Section II of this report examines selected short-term aerodynamic and propulsion modifications that might reduce the consumption of jet fuel in the existing fleet.

Section III examines the resources and technologies that might be used in the development of noncrude-oil-based aviation fuels in the long term. This focus is then narrowed to an evaluation of coal as a future source of jet fuels to highlight some of the energy, cost, and environmental aspects associated with the production of synthetic jet fuels.

Section IV then delineates the conditions under which it would be to the Air Force's advantage to develop a noncrude-oil-based propulsion capability and assesses the possible benefits of such a capability.

Section V draws conclusions based on the material contained in the preceding sections.

II. SHORT-TERM TECHNOLOGICAL MODIFICATIONS

The acquisition of a new fleet of aircraft involves numerous compromises between the performance characteristics believed to be necessary by the operator and the cost of applying and/or extending the state of the art of technology. These compromises are usually struck by identifying the threat, formulating a mission to counter that threat, and then evaluating alternative designs from the standpoint of their cost effectiveness and ability to complete the proposed mission. However, it frequently happens that after the airplane has been put into service, the nature of the threat changes and the perception of the mission requirement is altered, while the state of technology continues to advance. It is possible that the existing inventory of aircraft no longer provides an optimal match (in terms of minimum energy usage) between the available state of the technology and presently perceived mission requirements. Thus, in this section we examine some technological modifications that might reduce the energy needed to meet current mission requirements. We will consider modifications to propulsion systems and alterations of the aerodynamic characteristics of some existing aircraft.

PROPULSION SYSTEM MODIFICATIONS

Turbine engines on many of the aircraft in the Air Force inventory were developed from a 1950s technology base. For a number of aircraft, there are newer engines available with comparable performance characteristics. These newer engines, developed from the 1960s technology base, typically consume from 20 to 30 percent less fuel than their predecessors. On the surface, it would appear that retrofitting existing aircraft with this more recent generation of engines would result in both an energy and a cost savings for the Air Force. This seems to be substantiated in part by two historical precedents: The first concerns the case where American Airlines retrofitted the turbojet engines on the 707-120 with turbofan engines. The second case concerns an engine change when the B-52H model was produced. Note that this is not an

example of an engine retrofit. When the H series was produced, the Air Force switched from the turbojet (on the B-52G) to a more efficient turbofan engine.

The potential annual fuel savings from an engine retrofit program is illustrated in Fig. 8 (a modification of Fig. 6). Total Air Force

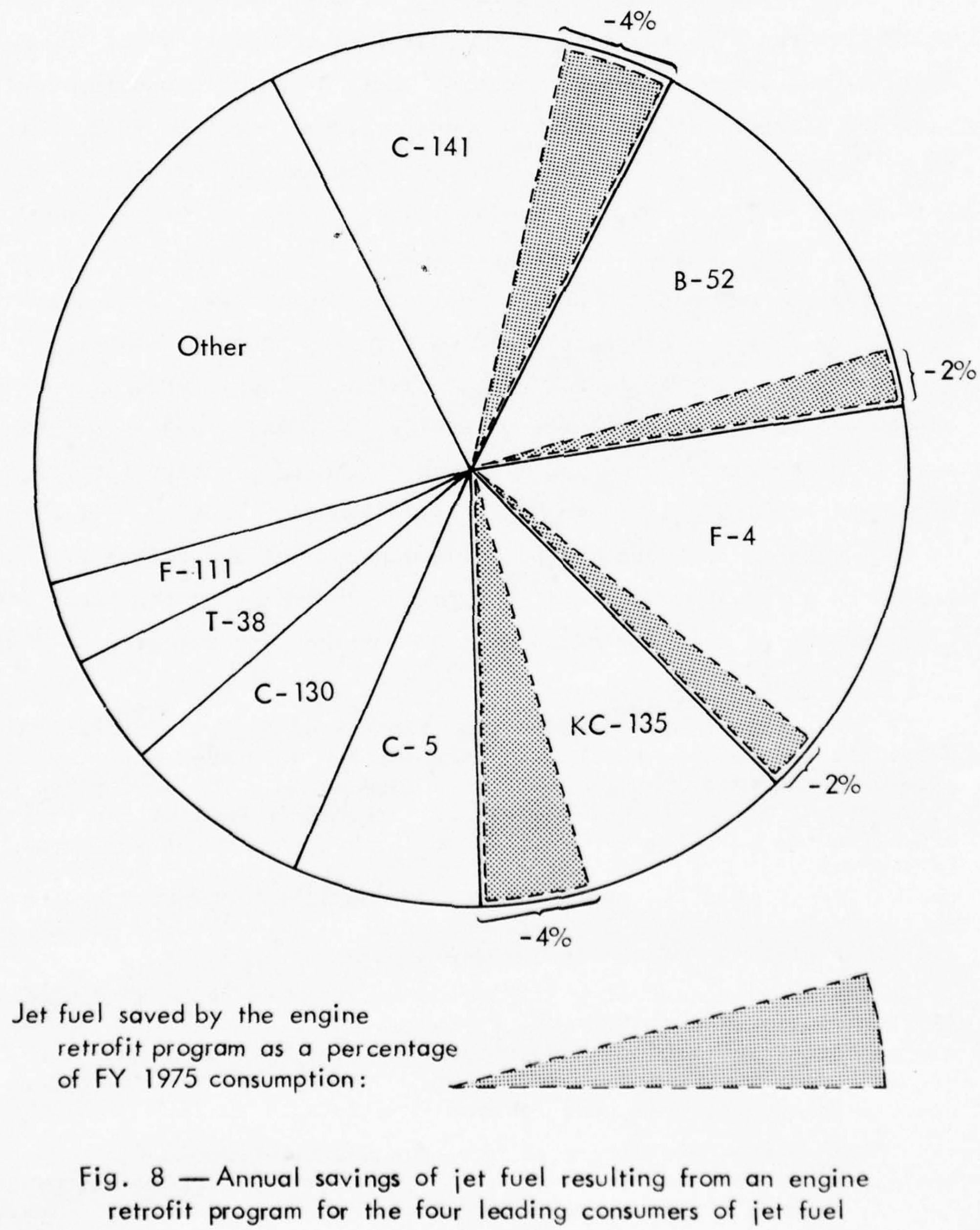


Fig. 8 — Annual savings of jet fuel resulting from an engine retrofit program for the four leading consumers of jet fuel

jet fuel consumption could be reduced by 12 percent if the engines were retrofitted on the leading four consumers of jet fuel (i.e., C-141, B-52, F-4, and the KC-135). In the next two subsections we will examine this idea.*

C-141 Engine Retrofit

It is estimated that by replacing the four TF33 engines on the C-141 with two TF39 engines, the annual fuel consumption for the C-141 could be reduced by about 25 percent. Such a retrofit program could save 190 million gallons of JP-4 annually (equivalent to 23.3 trillion Btu). At 35 cents per gallon, the reduction in the annual fuel cost for the C-141 fleet would be \$66.5 million. However, we also need to consider the cost of changing engines and the energy used in manufacturing the new engines and in modifying the aircraft to accommodate the new engines.† These costs and savings are presented in Fig. 9 for energy and in Fig. 10 for dollar savings. The figures display the energy and budget expenditures to modify the C-141 fleet as negative savings. For example, during the peak of the engine retrofit program, a quarter billion dollars would be spent annually from FY 1979 through FY 1981 with the assumed modification schedule of about five aircraft completed per month. The energy expended in modifying the fleet could be recovered by the last year (FY 1982) of the retrofit program,‡ as

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*The analysis considered a wide variety of engine retrofit candidates for the various aircraft. This section discusses only the most promising candidate for each aircraft considered. The JP-4 price of 35 cents per gallon (mid-1974 dollars) assumed in most of the cost-effectiveness calculations was the prevailing price at the time of this analysis. This 1974 price is equivalent to a first quarter 1977 fuel price of about 43 cents per gallon, using the observed general inflation rate of about 7.3 percent, or about 41 cents per gallon using the 6 percent inflation rate assumed in the analysis.

†The average cost of modification was assumed to be \$4.6 million (FY 1974 dollars) per aircraft, including RDT&E costs, start-up costs, engine costs, and airframe modification costs, to accommodate the higher thrust level of the new engines. Propulsion characteristics and energy expenditures were derived from Refs. 9 to 11.

‡The energy expenditure to make the modification would be in the commercial sector. Of course, the Air Force would realize energy savings as soon as the first retrofitted aircraft began flying. Thus, the cumulative net energy savings should be thought of in an overall national context.

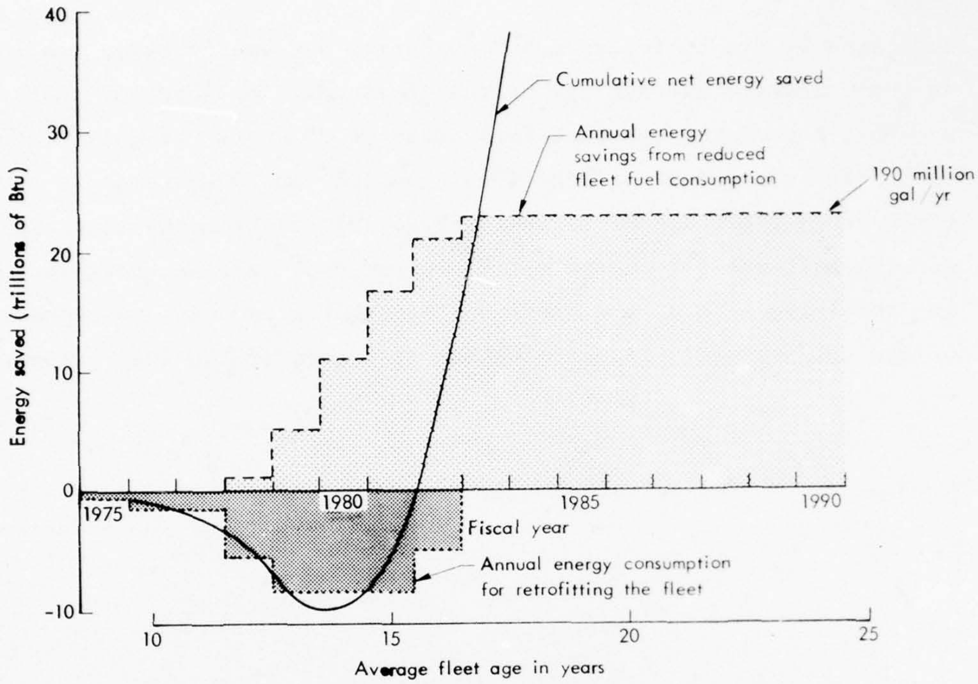


Fig. 9 — Energy impact of a C-141 engine retrofit program

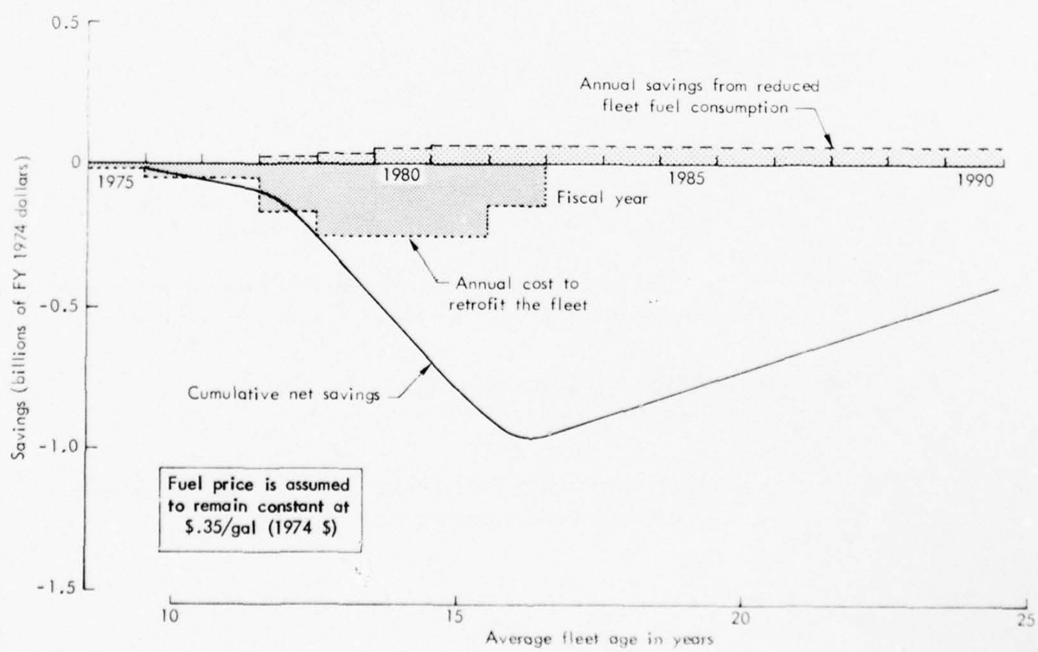
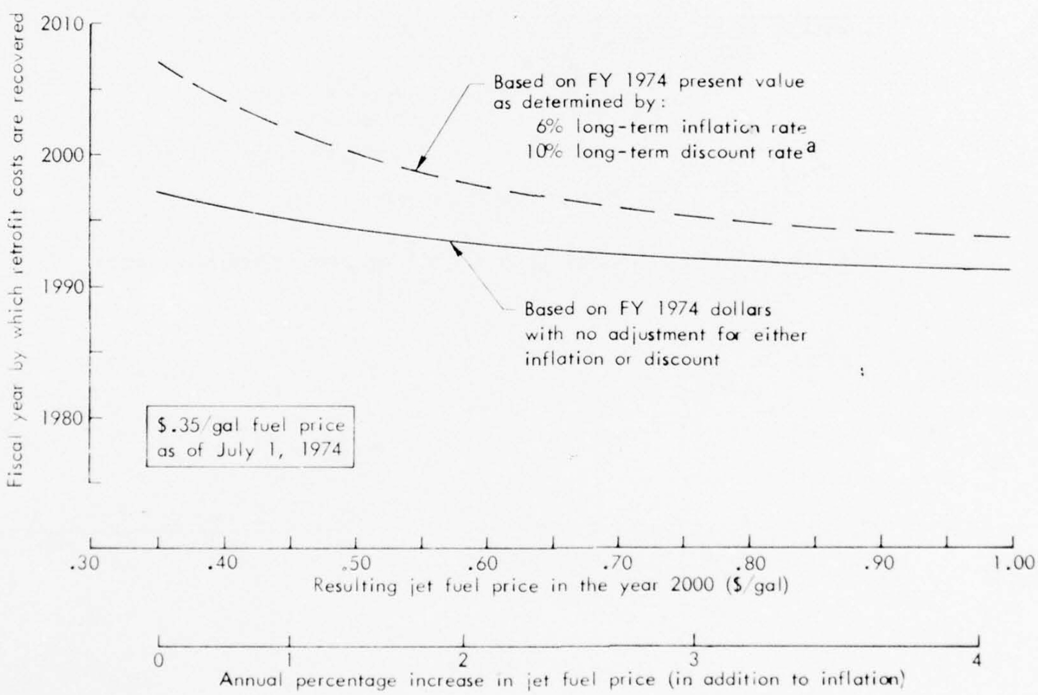


Fig. 10—Cost impacts of a C-141 engine retrofit program

indicated by the curve labeled "cumulative net energy saved" in Fig. 9. At that time the average age of the fleet would be about 15 years. However, assuming a constant fuel price of 35 cents per gallon, the cumulative net budget savings (undiscounted) would be negative beyond the average fleet age of 25 years (Fig. 10). This means that the budget expenditures for the retrofit program could not be recovered over the remaining life of the airplane through the reduced fuel consumption of the new engines. Figure 11 shows that even if the fuel price rises



[a] These assumptions yield a very conservative net discount rate of approximately 4 percent.

Fig. 11 — Effect of increasing fuel prices on the engine retrofit cost recovery year for the C-141

(at a constant percentage rate)* to a dollar a gallon (in 1974 dollars) by the year 2000, the retrofit costs would not be recovered until the early 1990s. At that time the average fleet age would be 25 years or more, depending upon whether the present value curve (dashed) or the undiscounted curve (solid) is used.

Other Engine Retrofit Candidates

Similar analyses were made of various engine retrofit modifications for the B-52G, KC-135A, and F-4C/D/E.† The results are generally the same as those for the C-141, except that it would take even longer to recover the retrofit costs (Figs. 12 and 13). In the case of the B-52G, we considered a retrofit that would replace the eight J57 turbojet engines with four TF39 turbofan engines and that would reduce the B-52 annual fuel consumption by about one-third. The KC-135A retrofit would involve replacing the four J57 turbojet engines with two TF39 turbofan engines. The F-4 retrofit would involve replacing the two J79 turbojet engines with two TF41 turbofan engines (modified to include an afterburner).

The results of the engine retrofit analysis are summarized in Table 1. Although there would be a net energy savings by the time each fleet reached an average age of 25 years, there would not be a net budget saving. This is generally due to three factors: the high cost of new turbine engines, the age of each fleet by the time the retrofit program is completed, and the comparatively low number of peacetime flying hours for military aircraft (as compared to commercial transports).

AERODYNAMIC CHARACTERISTICS

Airframe modifications that could reduce aerodynamic drag and hence reduce fuel consumption have been proposed for several Air Force aircraft. In particular, the Lockheed-Georgia Company has conducted

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*In addition to inflation.

†The average modification cost per aircraft was assumed to be \$5 million for the B-52G, \$4.3 million for the KC-135, and \$2.1 million for the F-4 (FY 1974 dollars).

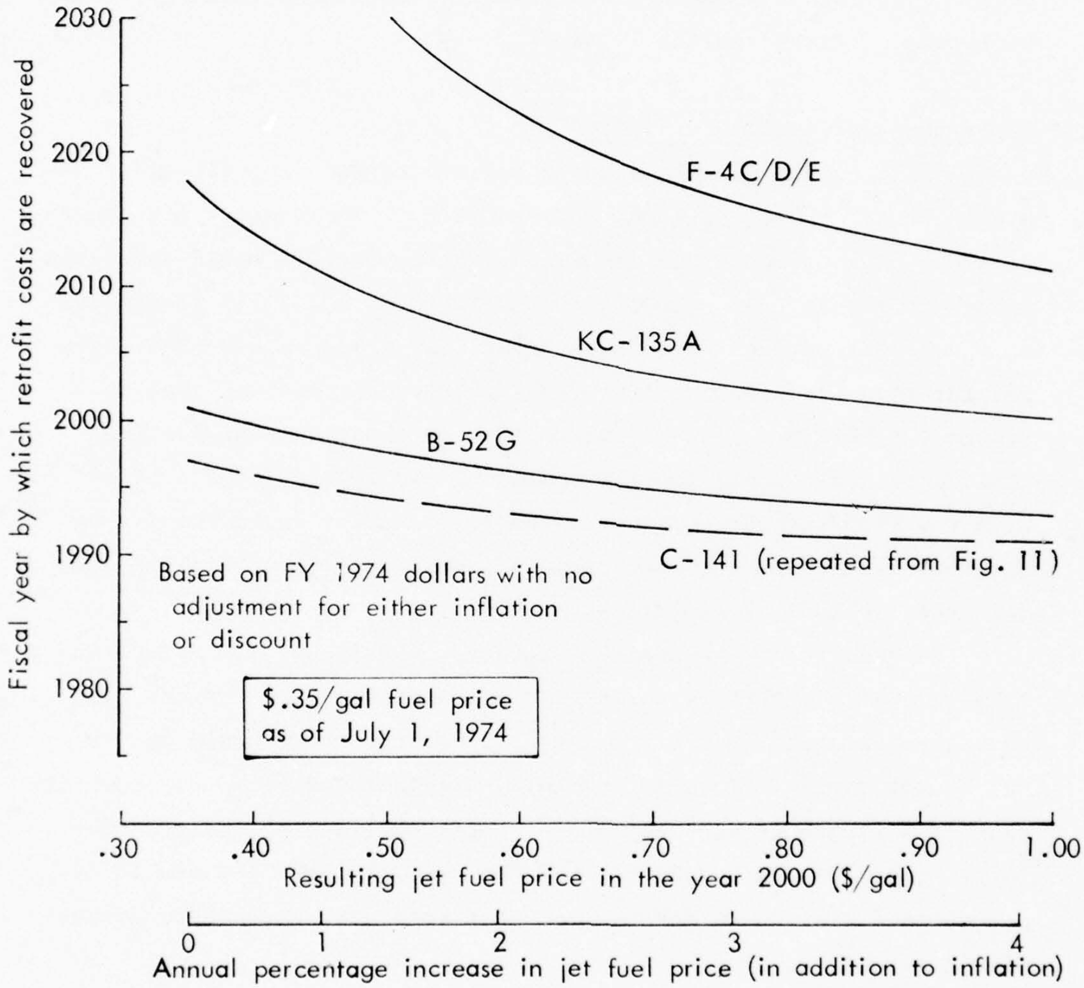

Fig. 12 — Effect of increasing fuel prices on the engine retrofit cost recovery year for the B-52G, KC-135A, and the F-4

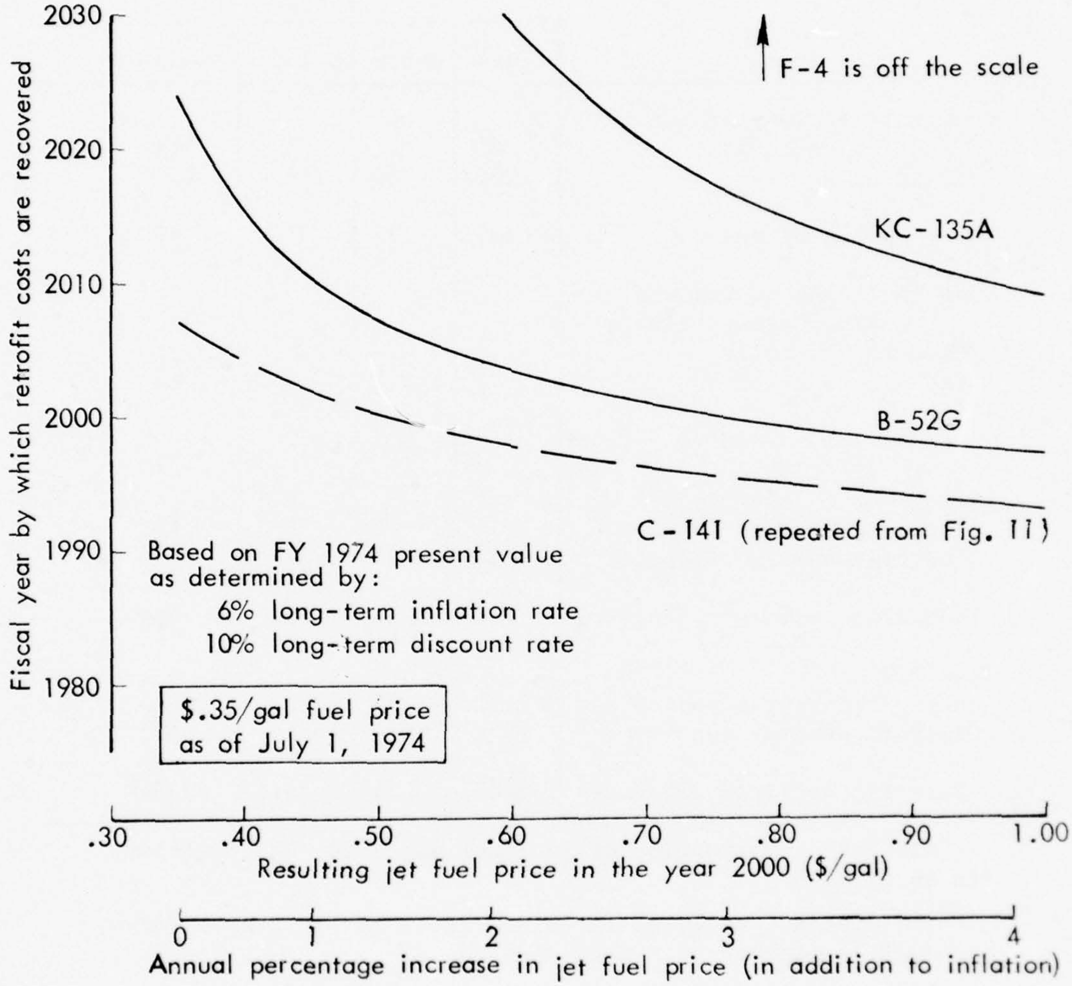

Fig. 13 — Effect of increasing fuel prices on the engine retrofit cost recovery year for the B-52G, KC-135A, and the F-4 (with consideration of discount rate and inflation)

Table 1

SUMMARY OF THE ENGINE RETROFIT ANALYSIS

Item	Fleet			
	C-141	B-52G	C-135A	F-4C/D/E
Energy (trillions of Btu[a])				
Used for retrofit	39	27	81	111
Saved by age 25	236	54	114	159
Net saving by age 25	197	27	33	48
Cost (billions of dollars FY 1974 present value[b])				
Used for retrofit	1.0	.7	2.0	2.7
Saved by age 25	.5	.2	.3	.4
Net saving by age 25	-.5	-.5	-1.7	-2.3
Average Fleet Age (years)				
Retrofit program completed	16	22	21	15
Retrofit energy recovered	16	23	25	21
Retrofit dollars[b] recovered	41	64	66+[c]	66+
Time (FY)				
Retrofit program completed	1982	1982	1982	1982
Retrofit energy recovered	1982	1983	1986	1988
Retrofit dollars[b] recovered	2007	2024	2033+[c]	2033+[c]

[a]Air Force consumption of jet fuel was about 476 trillion Btu in FY 1975.

[b]10% discount rate, 6% inflation rate, and fuel price of $.35/gal is assumed to remain constant.

[c]Dollars still not recovered at indicated age/time.

wind-tunnel tests and other supplemental analyses that indicate that modest drag reductions may be achievable by modifying the aerodynamic characteristics of the C-141A and C-130 transports. Determining the impact of these modifications is of particular interest, since these two aircraft consume about 22 percent of all Air Force jet fuel. Our major focus will be on a C-141A modification, since both performance and cost information are available for this aircraft; however, parametric cost/performance tradeoff curves for other Air Force aircraft

have been developed to gain further insights into the utility of aerodynamic modifications.

C-141A Wing Fillet and Vortex Generators

During the late 1960s, wind-tunnel tests by the Lockheed-Georgia Company indicated that removal of the vortex generators on the wing and an improvement in the design of the fillet at the wing/fuselage interface on the unstretched C-141A aircraft might reduce aerodynamic drag by about 8 percent--3 percent from removal of the vortex generators and the remainder from the improved fillet (Fig. 14).[12] The original cost estimate for these aerodynamic modifications was less than $100,000 (FY 1974 dollars) to modify each aircraft.*

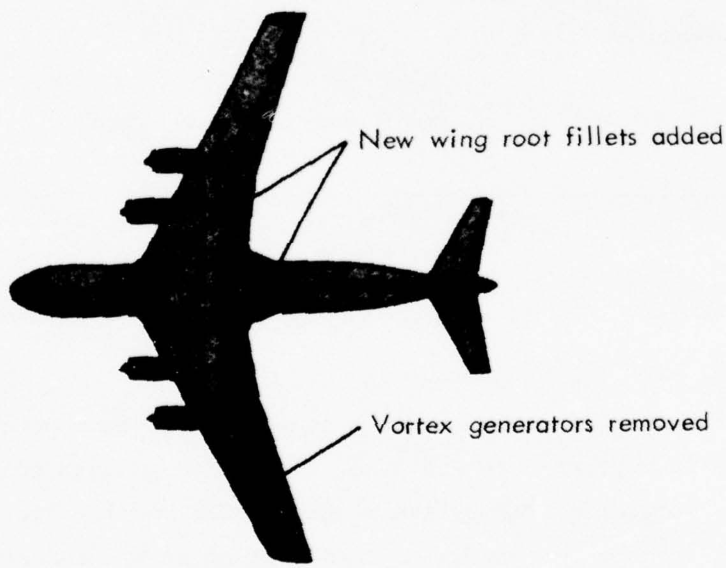

Fig. 14—C-141A drag reduction modifications (from Ref. 12)

Energy Efficiency. Figure 15 shows the impact on fuel consumption if the C-141A aerodynamic modification were made to the entire fleet over an eight-year period. (Note that the energy expenditure to

*Personal communication from William Lamar, Air Force Flight Dynamics Laboratory, 1974.

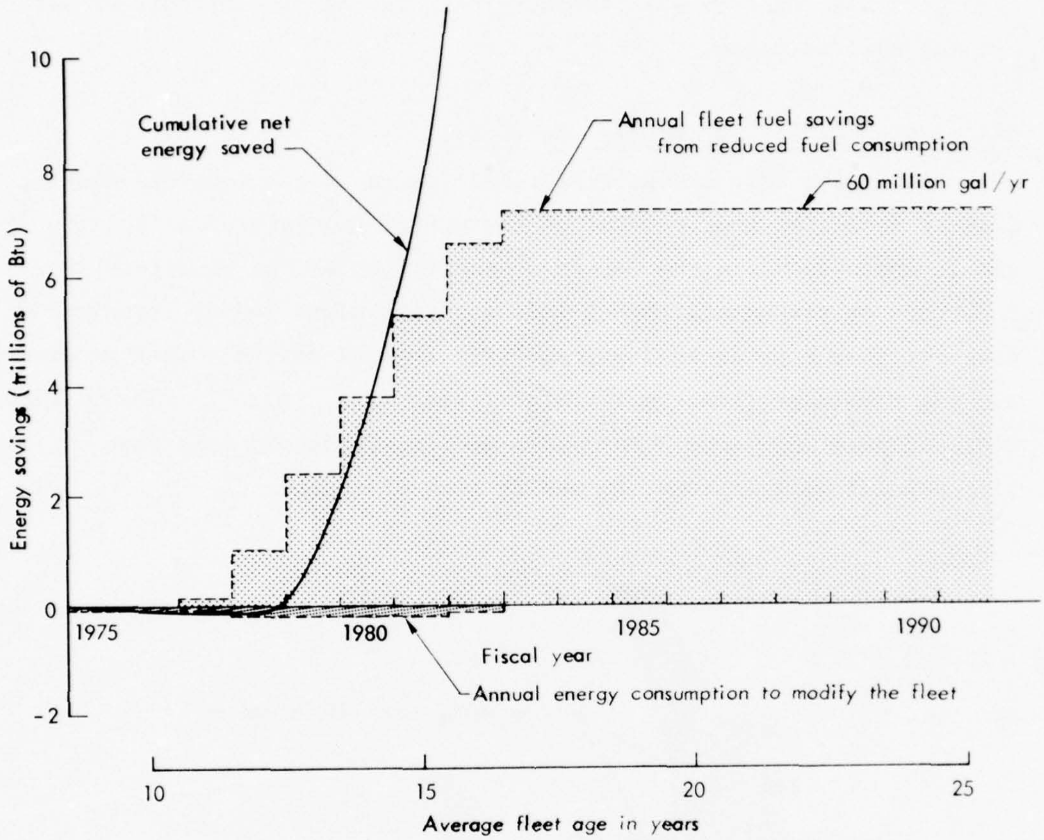

Fig. 15 — Energy impact of a C-141A aerodynamic modification

effect the modification would be quite modest.*) If an 8 percent reduction in consumption were achieved, 60 million gallons of jet fuel would be saved per year by the program. The modification program would produce net energy savings soon after its inception, and even at the completion of the program the fleet would still have a significant number of years of useful life remaining. Thus, we conclude that this aerodynamic modification would be highly energy-efficient.

Cost Recovery. Figure 16 shows the impact on the budget of a C-141A aerodynamic modification. Note that if the modification could be completed at a cost of about $120,000 per aircraft (including RDT&E expenditures), savings in jet fuel expenditures would allow recovery of the

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*Derived from Ref. 11.

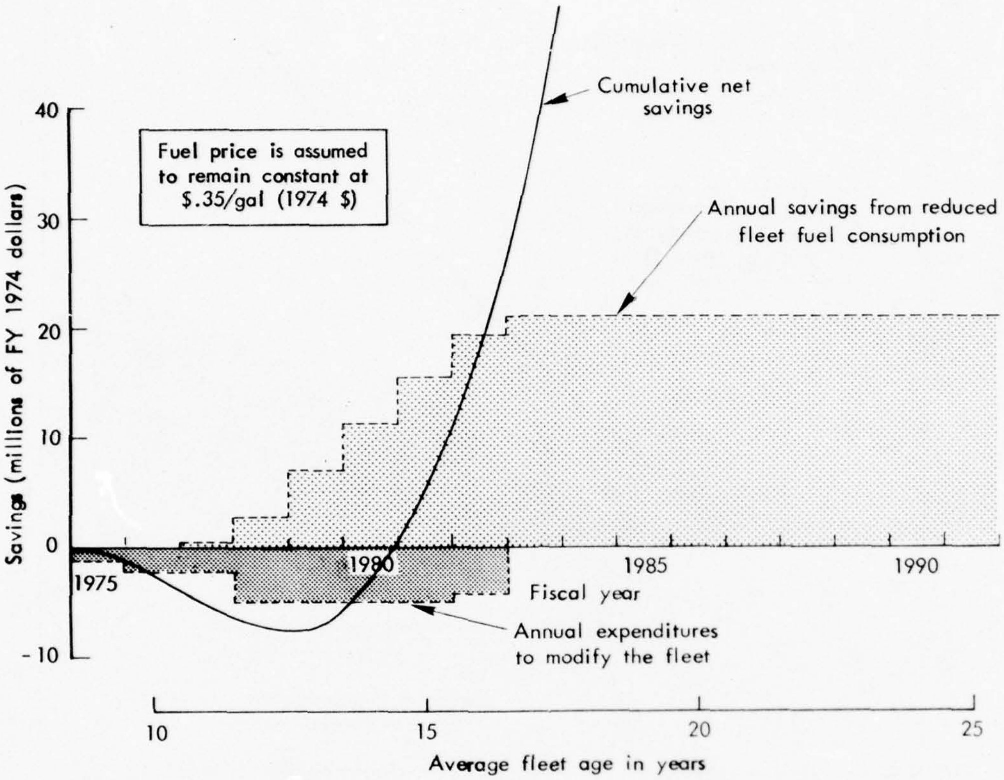

Fig. 16 — Cost impact of a C-141 aerodynamic modification

modification costs even before completion of the program. We conclude, therefore, that the proposed aerodynamic modification would clearly allow cost recovery at a modification cost per aircraft of $120,000.

Because cost estimates are inevitably subject to change, we have chosen to parameterize the cost recovery potential of an aerodynamic modification to the unstretched C-141A for a range of plausible modification costs and fuel consumption reductions (Fig. 17). Whether costs can be recovered through savings in fuel expenditures before the fleet is retired will depend upon the ultimate cost of the modification, its effectiveness, the service life of the aircraft,* and

*Considerable uncertainty exists regarding the ultimate service life of the C-141A. The Durability and Damage Tolerance Assessment Study currently being performed by the Air Force Logistics Command and Air Force Systems Command is attempting to evaluate the validity of the 40,000 hour service life estimate presently being used for

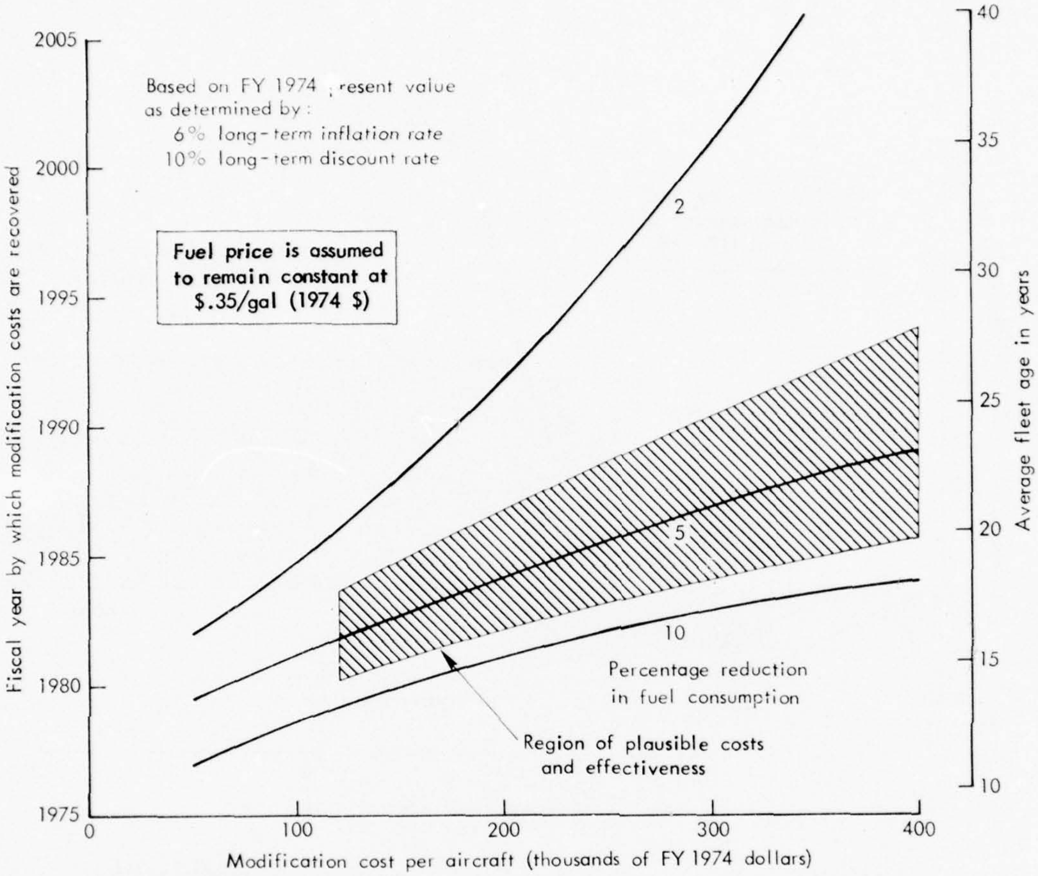

Fig. 17—Cost recovery potential for an aerodynamic modification to the C-141A

future escalations in fuel costs. Figure 17 indicates that if costs were to rise to $250,000 to $400,000 per aircraft to accomplish the modification, there would be some doubt as to whether cost recovery would be possible. Nevertheless, further exploration of the cost of an aerodynamic modification and a determination of the additional years the C-141A is to be kept in service seem desirable.

C-130 Afterbody

Lockheed has also analyzed, in considerably less detail than for the C-141, possible changes to the C-130 aircraft to decrease aerodynamic drag, and in so doing decrease fuel consumption. Some of the

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planning purposes. At current utilization rates, this 40,000 hour service limit translates to an average fleet life of approximately 31 years.

approaches considered include the addition of wing/fuselage fillets, refairing of the afterbody, vortex control on the afterbody, or moving pylon-mounted fuel tanks to the wing tips.[14] The analysis was originally motivated by a desire to increase the range of the Dedicated Electronic C-130s of the Navy.

Wind-tunnel tests have been made with strakes (or cusps) along the chine of the aircraft, in an attempt to reduce the pressure drag associated with the afterbody. It is important to note that this type of modification will not interfere with the operation of the aft cargo door. Preliminary results indicate that such a modification might reduce drag by about 3 percent. Lockheed engineers believe that more extensive wind-tunnel testing might result in modifications that would reduce drag slightly more. For those applications that do not require use of the aft cargo doors (USMC use of KC-130s), an extensive afterbody modification is available that would reduce drag an estimated 9 percent.*

Figure 18 shows the cost recovery potential of an aerodynamic modification to the Air Force C-130 fleet as a function of the modification cost per aircraft and the reduction in fuel consumption. For most reasonable sets of fuel consumption and cost assumptions, it appears that costs cannot be recovered through savings in jet fuel expenditures before the fleet has exceeded its useful life. This is a consequence of the fact that the average Air Force C-130 was already 14 years old in 1976. Thus, we conclude that the costs of an aerodynamic modification to the C-130 will most likely not be recovered through savings in jet fuel expenditures.

We also investigated an alternative modification strategy--one that would modify only the newer C-130s in the Air Force fleet. However, our results indicate that even if only the newest 25 percent of the Air Force C-130 fleet were modified, substantial reductions in fuel consumption and very low modification costs would be required, if costs were to be recovered. For example, the costs for a modification requiring a $135,000 expenditure per aircraft, yielding a 10 percent

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*Personal communication from Skip Bolling, Lockheed-Georgia Company, August 30, 1974.

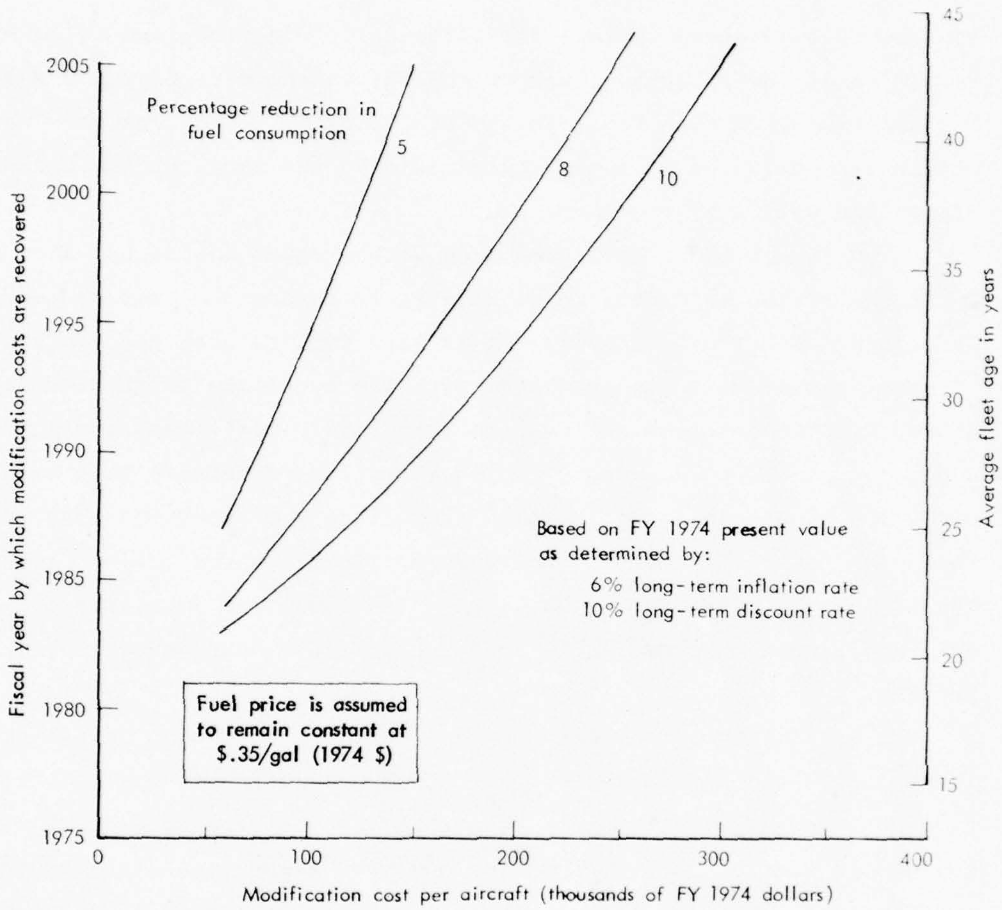

Fig. 18—Cost recovery potential for an aerodynamic modification to the C-130

reduction in fuel consumption, could be recovered at an average fleet age of 20 years (for the newest 25 percent of the fleet).

B-52 Modifications

The B-52 fleet, since it accounts for about 15 percent of Air Force jet fuel consumption, is yet another candidate for fuel conservation measures. In the event modifications are proposed for this fleet, we show in Fig. 19 the cost recovery potential for the Air Force B-52 G/H fleet as a function of the modification cost per aircraft and potential reduction in fuel consumption. The results indicate that only for relatively low-cost, highly effective modifications could costs be recovered before the useful life of the aircraft is exceeded.

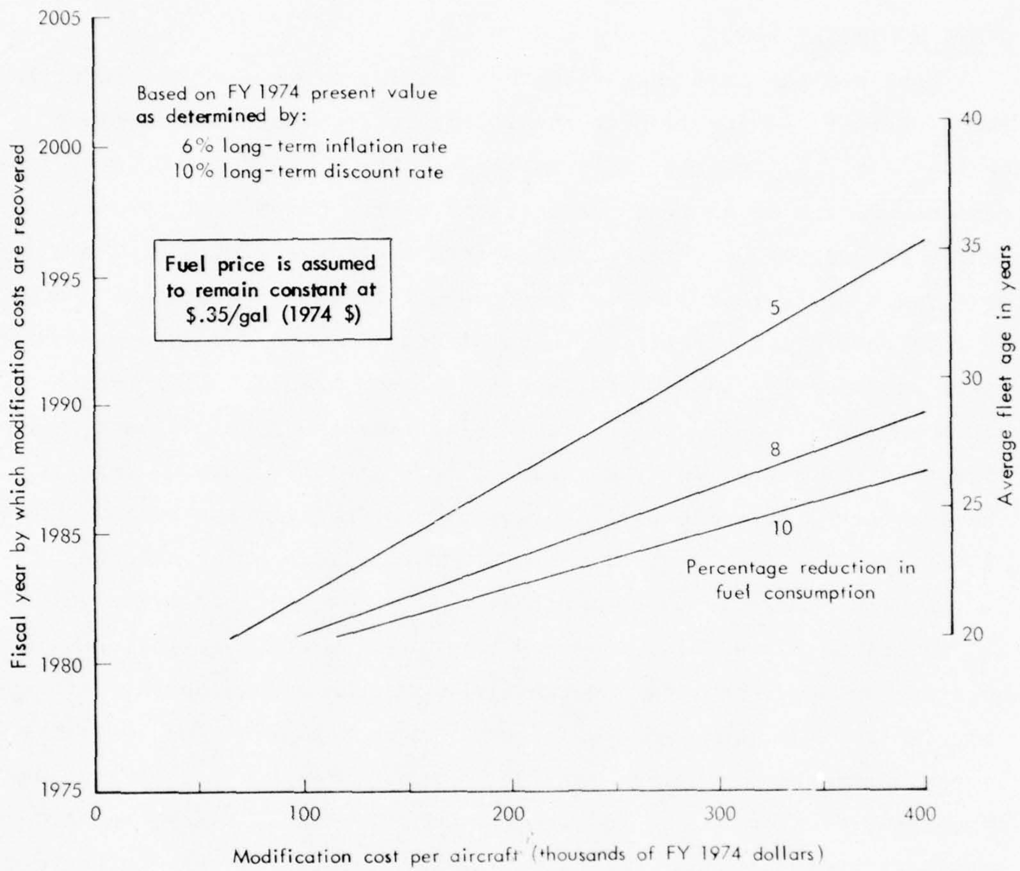

Fig. 19— Cost recovery potential for an aerodynamic modification to the B-52G/H

Winglets

Wind-tunnel tests of wingtip devices termed "winglets" have indicated that drag reductions on the order of 5 to 10 percent may be achievable for transport-class aircraft. The Air Force and NASA are currently installing winglets on a KC-135 test bed to investigate the drag reduction potential of such an aerodynamic modification.(15) Any assessment of the cost recovery potential and energy efficiency of winglets will have to await the results of the flight-test program. However, in the event such a modification is subsequently suggested for the C-141, C-130, or B-52, the parametric results shown in Figs. 17, 18, or 19 can be used to gain insights into the cost recovery potential of a winglet modification.

OTHER MODIFICATIONS

Lockheed has also suggested that loading cargo aircraft such that the center of gravity is near the allowable aft limit could reduce cruise drag. Apparently, this may reduce the drag of the C-5A by 1.6 percent, of the C-141 by 2 percent, and of the C-130 by 1 percent, assuming the center of gravity shifts from about the middle of the allowable range to the aft limit. One drawback of this operational change is that the flying qualities of the aircraft may be degraded--the aircraft may tend to "wander" because it is less stable. This effect has been confirmed in the Dedicated Electronic Navy C-130s, which nearly always fly with the center of gravity near the aft limit.* Despite the drawbacks, this modification appears potentially attractive, since it offers reductions in fuel consumption at little or no expense.

We can summarize by noting that all of the short-term technological modifications we have examined appear to be energy-efficient. In general, engine retrofits save more energy than modest aerodynamic modifications. The engine retrofit option does not allow full recovery of costs through savings in jet fuel expenditures because of the huge investment costs required to make the modification. Hence, any proposal attempting to justify the cost effectiveness of the engine retrofitting option will have to do so not solely in terms of reduced expenditures for jet fuel, but also in terms of possible operational advantages offered by enhancements in capability (e.g., greater range) that the option might permit.

Aerodynamic modifications could allow full recovery of costs through savings in jet fuel expenditures if made early in the life cycle of an aircraft. Further study of the C-141A modification seems warranted; however, an aerodynamic modification to the C-130 fleet does not appear to be an attractive option, unless only the newer aircraft in the fleet are modified. While the prospects of conserving energy while fully recovering modification costs through reduced fuel expenditures do not appear altogether attractive for the aforementioned

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*Personal communication from Tom Blackby, Lockheed-Georgia Company, August 30, 1974.

aircraft, the relatively lower cost of simple aerodynamic modifications (as compared to engine retrofits) and the potential reductions in fuel consumption (5 to 10 percent) lead us to conclude that modifications may be viable for future aircraft if they are accomplished early enough in the aircraft life cycle to allow cost recovery.

With this background on the energy and cost impacts of short-term technological modifications to reduce fuel consumption, we will now consider the long-term prospects for using alternative aviation fuels. The assessment begins in Sec. III with an examination of the energy resources and production processes from which future jet fuels may be derived. The production of jet fuels derived from coal, the nation's most abundant fossil resource, is then examined in some detail to highlight some of the major cost, energy, resource, and environmental issues associated with synthetic jet fuel production. Section IV then delineates the conditions under which it would be to the Air Force's advantage to develop the synthetic jet fuel option for the future and assesses the possible benefits from possessing a synthetic jet fuel capability in the future.

III. ALTERNATIVE JET FUELS

INTRODUCTION

The ominous prospect of declining domestic petroleum supplies in the future and the uncertainties associated with the economics of those supplies pose a distinct challenge to the Air Force, which relies totally on petroleum for its jet fuel needs. The Air Force will be bidding for liquid fuels in a highly competitive U.S. transportation market which today derives over 95 percent of its energy needs from petroleum, accounting for about 56 percent of total U.S. petroleum consumption (nearly equal to all domestic petroleum production), and about 25 percent of total U.S. energy consumption.(16)

There are strong indications that the demands of the transportation sector alone for liquid fuels from petroleum will significantly exceed U.S. domestic production by the end of the century. Estimates developed by ERDA indicate a substantial shortage of liquid fuels in the future, even with the development of the outer countinental shelf and Alaskan crude-oil reserves and enhanced recovery techniques (Fig. 20). Depending on the ultimate success of these efforts and the extent to which more fuel-conservative vehicles are introduced, the shortage might range from roughly 5 to 12 million barrels per day by the year 2000. The demands by other sectors for petroleum, accounting for 44 percent of consumption today, will further exacerbate the liquid fuel shortage. To meet demands, aggressive energy conservation efforts and development of alternatives to petroleum will be required. If these efforts fail, we will face the undesirable alternative of relying even more on crude-oil imports to satisfy our energy needs.

From an Air Force perspective, any new source of energy for aircraft will have to be derivable from an abundant energy source, be economic, be easily portable in a liquid state, have a high heat of combustion, and be suitable for use in military engines. This section begins by examining the domestic energy resource alternatives to crude oil that might be used in the future production of jet fuels, by identifying the most attractive jet fuel forms derivable from these resources,

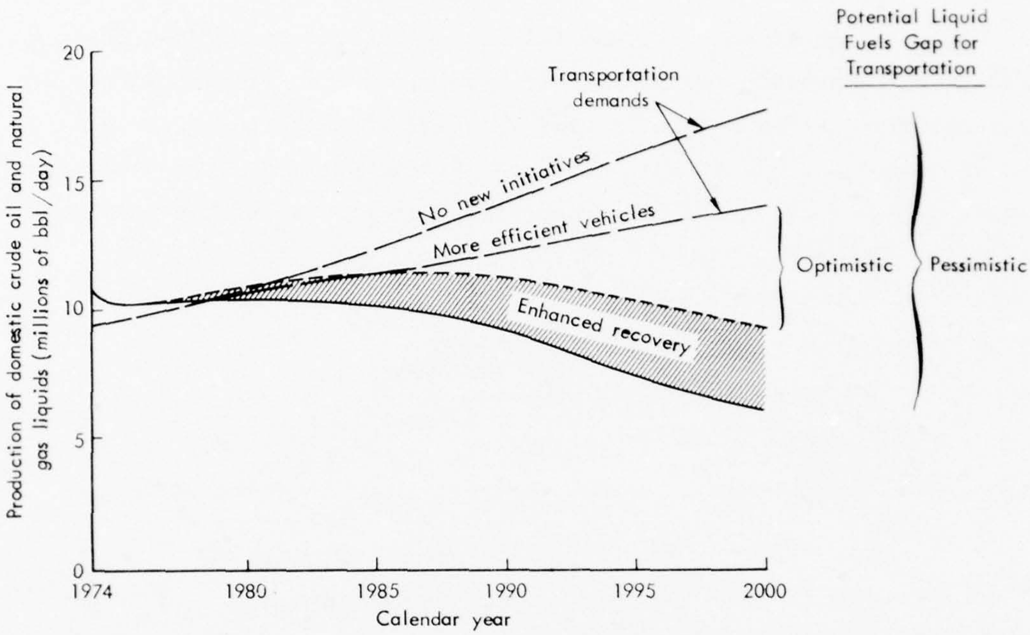

Fig. 20 — ERDA projections of U.S. crude-oil supply and transportation demands (from Refs. 17 and 18)

and by describing the production processes that might be used to produce jet fuels from domestic resources. The production of the three most attractive jet fuel candidates derivable from coal are then compared in terms of cost, energy requirements, resource requirements, and environmental impacts, to highlight some of the major issues associated with synthetic jet fuel production. The section concludes with a discussion of the R&D areas that would have to be pursued to provide a synthetic jet fuel option for the future.

ENERGY RESOURCES FOR JET FUELS

The spectrum of potential domestic energy resource alternatives to crude oil and natural gas is sizable. However, the extent to which these alternatives will replace or supplement diminishing crude oil and natural gas supplies will depend critically on the development of technology to extract useful energy from these resources in an economic and environmentally acceptable manner. Domestic energy resources can be grouped into two very broad categories: (1) the carbonaceous resources

(those containing carbon), and (2) the noncarbonaceous resources. Each of these categories may be further subdivided into resources that are essentially inexhaustible or renewable and those that are essentially nonrenewable (at least when measured in time periods of hundreds rather than millions of years) (see Fig. 21).* In principle, hydrocarbon

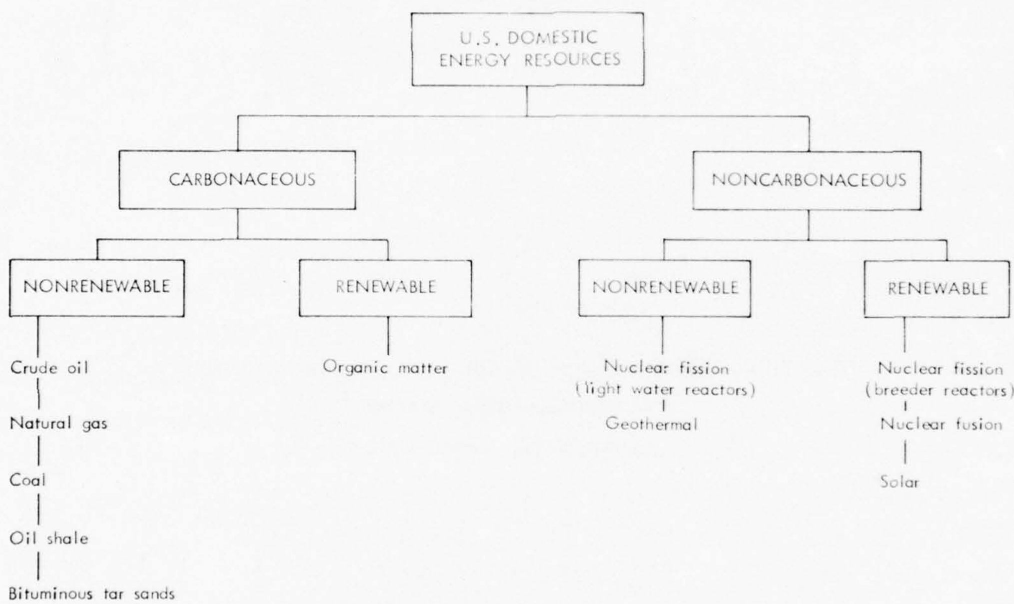

Fig. 21 — Categorization of U.S. domestic energy resources

fuels can be obtained solely from carbonaceous energy resources or in combination with noncarbonaceous energy resources. Hydrogen fuel can be obtained, in principle at least, from any of the sources shown in Fig. 21.

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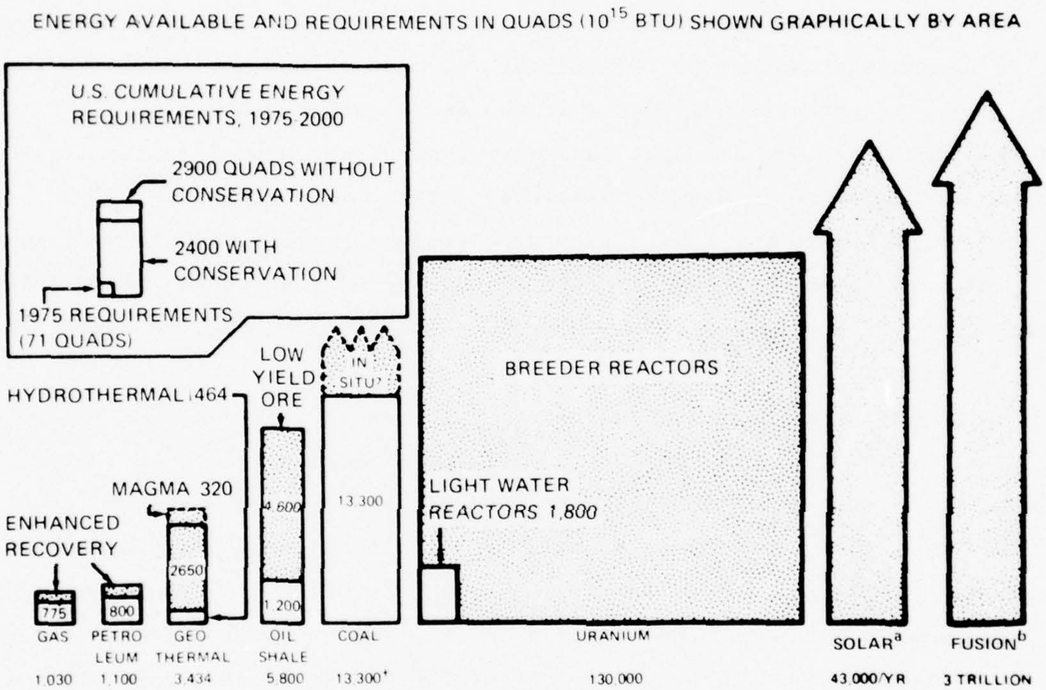
*Recognize that there is some degree of arbitrariness in this classification scheme. Carbonaceous nonrenewable energy resources could be considered renewable over time periods of millions of years. Likewise, some fissionable resources are finite, as are lithium and deuterium used in the fusion reaction; nuclear fission from breeders and nuclear fusion could be considered nonrenewable energy sources when measured in thousands to billions of years. Ambiguities exist with regard to various sources of geothermal energy as well.

Figure 22 shows ERDA's interpretation of domestic U.S. energy supplies.* Several compelling messages are apparent from an examination of Fig. 22 and consideration of present U.S. energy consumption patterns.



NOTE: Shaded areas indicate additional resources that may become recoverable if suitable technologies are developed.

[a]Represents the total average solar flux incident on the United States per year

[b]Total potential energy that could be derived from the deuterium in the world's oceans.

Fig. 22 — Potentially recoverable domestic energy resources (from Ref. 4)

First, while the United States is richly endowed with energy resources capable of supplying energy needs for many years to come, the nation currently relies heavily on a narrow and declining resource base of crude oil and natural gas for 74 percent of its energy needs.+ Consideration of the alternatives to crude oil and natural gas indicates that

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*The interested reader is referred to the appendix for more details about the extent, distribution, and characteristics of the domestic energy resource base.

+Derived from Bureau of Mines and Edison Electric Institute data for 1975.

oil shale and coal are the nation's most abundant fossil resources. As will be discussed below, technologies have been and are being developed for converting these solid resources to gaseous and liquid forms suitable for processing into jet fuels.

The ultimate size of the uranium resource base depends on the type of technology assumed to be available to convert the uranium to useful energy. Figure 22 indicates that the introduction of breeder reactors that could convert abundant but nonfissionable uranium-238 into fissionable isotopes could dramatically expand the energy recoverable from our uranium resource base. From an aviation perspective, the most immediately apparent application of nuclear-generated heat or electricity would be in the production of hydrogen--one aviation fuel candidate for the future.

Solar energy and fusion hold the promise of providing virtually limitless energy supplies for the future, *if* economical technologies can be developed to cope with the intermittent and low energy value of the solar flux, and the formidable problems of controlling thermonuclear reactions. Energy from these resources would also probably be most easily exploited for aviation in the production of hydrogen fuels.

Department of Interior estimates of U.S. tar sand deposits (an energy resource not explicitly mentioned in Fig. 22) indicate that the recoverable energy content of U.S. tar sands would amount to, at best, perhaps 83 quadrillion Btu--less than 10 percent that of any of the other resources shown in Fig. 22.[19,20] Hence, it seems unlikely that U.S. tar sands could ever constitute the basis for any large domestic synthetic fuels industry.

Deriving energy from organic matter (e.g., waste products, energy crops), another energy resource not mentioned in Fig. 22, is just one of the means by which the solar flux can be harnessed to provide useful energy (e.g., wind generators, tides, hydropower, photovoltaic conversion, central station thermal electric generation). However, it is distinguished from many of the other solar technologies in that it provides an alternative carbonaceous energy source to fossil fuels that is renewable. The potential contribution of this component of solar energy technology to future energy supplies will have to await resolution of technical and economic uncertainties.

We can summarize this overview of domestic energy resources by noting that the energy resource alternatives to crude oil and natural gas are many; however, the ultimate recovery and use of each of these alternatives over time will be dictated by the development of economical technologies to supply this energy to energy consumers, including the military.

PROSPECTIVE JET FUELS

Background

Used either singly or in combination with other energy resource alternatives to crude oil, the resources just described can be processed into a wide variety of alternative jet fuels. The extensive list of fuel candidates in Table 2 was narrowed down to three alternatives by (1) examining the comparative physical properties of the fuels in the context of aviation applications, and (2) developing conceptual aircraft designs for the most promising alternatives to evaluate their performance.* One of the primary driving mechanisms in reducing the list of viable candidates was the very low gravimetric heats of combustion (heat content per pound) of many of the fuel candidates (e.g., ammonia, methanol, and hydrazine). This undesirable physical characteristic resulted in aircraft gross weights far in excess of those using the most attractive fuels. To a lesser extent, the energy required for production, cost considerations, and technical difficulties in fuel production also reduced the list of viable fuel alternatives. In particular, for the cases of acetylene and propane, which have gross characteristics similar to JP-type fuels, we were unable to identify any synthesis processes in which either of these relatively complex hydrocarbons could be manufactured at a lower unit energy cost than that projected for a JP fuel.

As a result of the screening process, three fuels were tentatively identified as being the most attractive--liquid hydrogen, liquid methane, and a synthetic jet fuel that might be similar to either naphtha-based

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*The reader is referred to Ref. 8 for the details of this screening process.

Table 2

PROPERTIES OF CANDIDATE FUELS

Fuel	Heat of Combustion		Density (lb/ft^3)	Boiling Point (°F)	Autoignition Temp. in Air (°F)	Flammability Limits in Air (%)
	Btu/lb	Btu/gal				
Acetylene (C_2H_2)	20,700	106,900	38.6	-119	635	2.5-80.0
Ammonia (NH_3)	8,000	45,600	42.6	- 28	1204	15-27
Ethanol (C_2H_5OH)	11,600	76,600	49.4	173	--	3.3-19.0
Hydrazine (N_2H_4)	7,200	60,100	62.4	236	518	4.7-100
Jet-Fuel (JP-4) (Naphtha-like)	18,700	121,100	48.7	210	480	0.8-5.6
Jet-Fuel (JP-8) (Kerosene-like)	18,600	128,300	51.6	400	450	0.6-5.0
Liquid Hydrogen (LH_2)	51,600	30,400	4.4	-423	1085	4.0-74
Liquid Methane (LCH_4)	21,500	74,400	25.9	-259	1000	5.0-15
Methanol (CH_3OH)	8,600	58,100	50.5	149	867	6.7-37
Monomethylamine (CH_3NH_2)	13,500	76,700	42.5	45	806	5.0-21
Propane (C_3H_8)	19,900	97,100	36.5	- 44	--	2.1-9.4
Gasoline[a] (C_8H_{18})	19,100	111,800	43.8	257	--	1.1-7.0

SOURCE: Ref. 8.

[a]Included for reference only.

jet fuels (e.g., JP-4, JET-B) or kerosene-based jet fuels (e.g., JP-5, JP-8, JET-A) in use today as derived from crude oil. Before describing some of the processes by which these fuel candidates may be produced, we first briefly discuss some of the physical properties of the fuels.

Liquid Hydrogen

Recent interest in hydrogen as a fuel has resulted from the growing awareness that our current fossil energy resources are indeed finite. Consequently, because hydrogen can be produced from water--a renewable and universal raw material--using relatively inexhaustible energy sources such as nuclear fission (given the development of breeder reactors), nuclear fusion, or solar energy, it has been suggested that hydrogen may be the universal fuel of the future. The concept of an energy industry based on using hydrogen for energy storage, distribution, and utilization has been termed "The Hydrogen Economy."[21]

Under standard conditions hydrogen is a colorless, odorless, nontoxic gas. In its liquid state, hydrogen requires sophisticated cryogenic storage, because of its very low boiling point. Given the excessive weight penalties associated with storing hydrogen in its gaseous form, or in a metal hydride, cryogenic storage of liquid hydrogen appears to be the only viable method for using hydrogen in aircraft applications using current or foreseeable technology.[22]

Perhaps the most attractive property of liquid hydrogen for aviation applications is its high gravimetric heat of combustion. Since the heat of combustion is nearly 2.8 times that of JP-4, the specific fuel consumption of the hydrogen engine is therefore reduced by approximately that factor, so aircraft fuel weight is accordingly reduced. These weight savings can translate into energy savings in aircraft operations; however, the energy required to produce and distribute the liquid hydrogen must also be considered. This subject is addressed later in this section.

Liquid hydrogen also offers some other advantages not apparent from the few physical properties noted in Table 2. The high specific

heat of hydrogen might allow it to be used as a heat sink for aircraft and engine cooling. The heat from the hot engine and aircraft parts could be transferred to the hydrogen fuel via a heat exchanger before it entered the combustion chambers, thereby forming a regenerative, no-loss cooling system, which could result in smaller, lighter, and more efficient engines, further reducing specific fuel consumption and aircraft fuel weight beyond that due to the high heat of combustion.

Experts also estimate that the purity of liquid hydrogen and the fact that it can be injected into the combustor in gaseous form might significantly improve the life of gas turbine components and reduce maintenance requirements. The rapid mixing and diffusion characteristics of hydrogen in air promote smooth ignition and uniform temperature profiles that could reduce thermal stresses in metal parts. The low emissivity of the hydrogen flame could also reduce metal temperatures. All of these qualities might tend to impose a less rigorous operating condition on the liquid-hydrogen-fueled engine than on a JP-fueled engine of comparable performance.[23]

The comparative safety of liquid hydrogen and conventional aircraft fuels is a controversial issue. When liquid hydrogen spills or leaks, the fuel immediately vaporizes and dissipates rapidly into the air, unlike conventional hydrocarbon fuels. Conversely, the wide flammability limits of hydrogen and low energy levels required for its ignition would call for careful handling by skilled personnel. Coping with the boil-off from cryogenic tank storage would also require procedures far different from those used for conventional fuels. Liquid hydrogen has, however, been routinely handled in the U.S. space program by skilled personnel without serious accidents for many years.[23]

Perhaps the greatest disadvantage of liquid hydrogen is its low density, requiring nearly four times the tank volume as a JP-type fuel to carry an equivalent amount of energy. Such increases in tank volume may result in increased drag, reduced lift-to-drag ratios, and tank configurations not commonly used on JP-fueled aircraft. This characteristic also probably limits the use of liquid hydrogen to transport-class aircraft. Despite the drawbacks, airframe manufacturers feel there are no major airframe or propulsion technological impediments to the

development of a liquid-hydrogen-fueled subsonic transport in the next 15 years.*

Liquid Methane

Methane, the primary constituent of natural gas produced in the United States, has found great use both as a clear burning gaseous fuel and as a chemical feedstock. The importation of liquefied natural gas (LNG), the fuel form in its cryogenic state, has increased significantly in recent years as domestic natural gas production has diminished.

Methane, a gas under standard conditions, is colorless, odorless (without the addition of odorants), and nontoxic, except as an asphyxiant. It has a gravimetric heat of combustion about 15 percent greater than that of conventional petroleum-based jet fuels, but this is offset by its 40 percent lower volumetric heat of combustion, a consequence of its low density. As with liquid hydrogen, the cryogenic form of methane would require fuel tank designs and handling techniques different from those used for more conventional liquid fuels. Liquid methane, when spilled, does not diffuse as rapidly as hydrogen because of its greater specific weight at standard conditions, which could represent a greater safety hazard.

Synthetic JP

JP-4 and JP-5 are the military designations for the petroleum-based jet fuels currently used by the Air Force and the Navy, respectively. JP-8 is a new military jet fuel similar in characteristics to kerosene-based jet fuels such as JET-A-1 used by commercial air carriers. Inclusion of existing JP fuels in Table 2 is not meant to imply that synthetic jet fuels derived from sources other than petroleum will exhibit physical and chemical properties identical to those in

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*Personal communications from G. Daniel Brewer, Russ Hopps, R. L. Dickinson, Russell Sessing, and Don L. Kelley, Lockheed-California Company, October 1974, and from P. E. Whitener, R. B. Brown, and D. G. Andrews, Boeing Aerospace Company, Seattle, Washington, October 16 and 17, 1974.

use today, but rather it is meant to indicate that synthetic jet fuels may be similar to naphtha-based wide-cut* jet fuels, such as JP-4, or kerosene-based narrow-cut* jet fuels, such as JP-5 or JP-8.

The USAF Scientific Advisory Board Ad Hoc Committee on Future Air Force Energy Needs has recommended that the Air Force make the transition from JP-4 to JP-8. This recommendation was prompted by the considerable competition that exists for the naphtha fraction of crude oil, particularly for the production of low-lead and lead-free gasoline and for petrochemical feedstocks, which is driving the costs of naphtha-based JP-4 into the premium fuel category.[24] A recent DoD directive has been issued prescribing that all new turbine-powered aircraft be designed to operate on JP-8, as well as on JP-5 and JP-4, which should give the DoD more flexibility in procurement of aviation fuels in the future.[25]

A synthetic jet fuel with characteristics similar to the kerosene- or naphtha-based jet fuels in use today probably represents the best compromise between volumetric and gravimetric heats of combustion of any of the fuels noted in Table 2. The fact that such a fuel would also be largely compatible with existing patterns of jet fuel storage, distribution, and use also makes a synthetic JP fuel attractive.

FUEL PRODUCTION PROCESSES

Overview

A multitude of possible techniques exist for producing the three synthetic jet fuel candidates from the various U.S. domestic energy resources. Figure 23 illustrates a representative, but by no means exhaustive, set of techniques for producing the fuels from energy resource alternatives to diminishing reserves of domestic crude oil and natural gas. Note that several of the primary energy resources, including coal, could, in principle, be used to produce any of the jet

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*Wide-cut and narrow-cut refer to the boiling temperature range over which each fuel is recovered during the distillation of the crude-oil product (whether it be a petroleum crude or a synthetic crude derived from coal or oil shale).

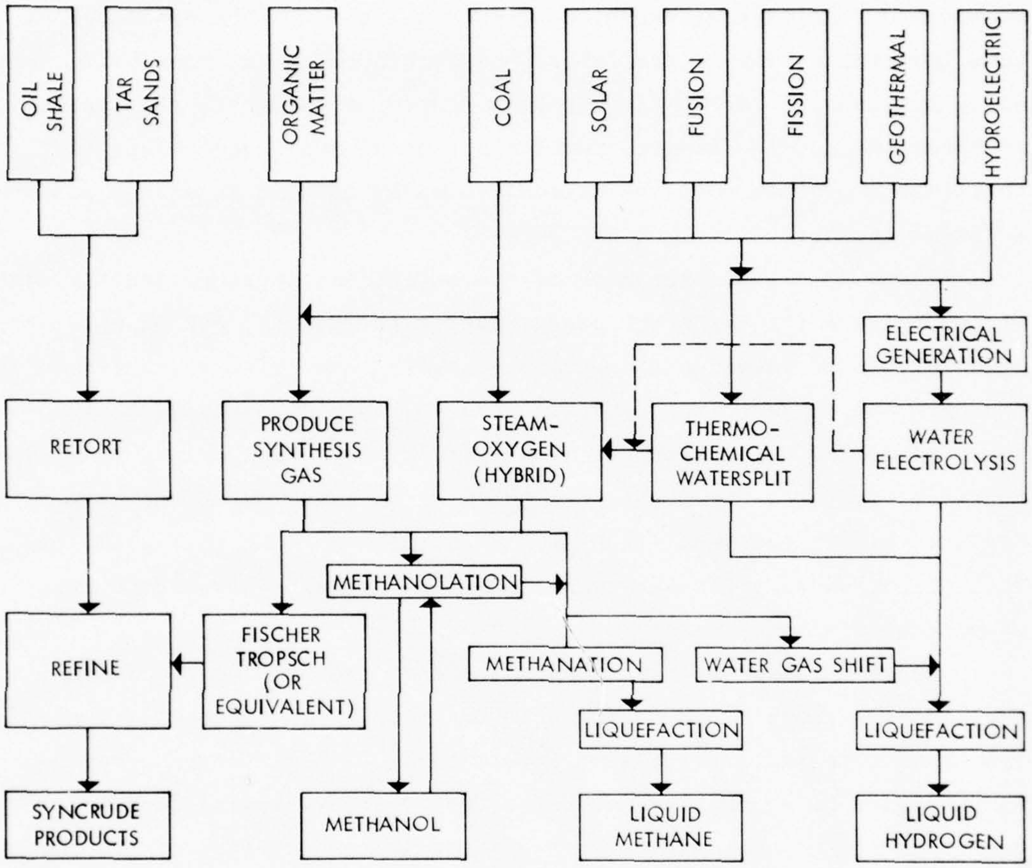

Fig. 23—Overview of synthetic fuel production processes

fuels of interest. Oil shale could also assume such a role, although attention thus far has focused on deriving premium liquid crude feedstocks from oil shale.

Note also in Fig. 23 that hydrogen can be derived from water using any of the energy resources that many postulate will be the ultimate major sources of energy for the United States and the world (e.g., solar, nuclear fusion, and nuclear fission). This attribute may become increasingly important at some time in the indeterminate future when fossil resources may become too valuable to use for energy purposes.

The production of the hydrocarbon fuel alternatives, synthetic JP and liquid methane, from renewable resources is more limited. In particular, a long-term commitment to the use of biomass or waste products

seems to be the only alternative if fossil fuels are not available at some indefinite time in the future. This discounts the possibility of using atmospheric carbon dioxide as a source of carbon in the synthesis of these fuels. The limited investigations of this concept suggest that such a process would be extremely costly both in an energy and in a fiscal sense.[26,27]

Figure 23 illustrates some of the potential opportunities for synergism between the different energy supply processes. For example, the electrolysis of water using nuclear-generated electricity results in hydrogen and oxygen. The hydrogen might be used directly as a gaseous fuel, liquefied for transportation applications, or pipelined to a conventional refinery for use in the refining of crude oil. The oxygen produced by electrolysis might profitably be used in a coal gasification plant, where air separation facilities normally constitute a major component of plant costs.

When one considers the resource base of each of the resources in Fig. 23, the present and foreseeable technology for converting these resources into the jet fuels of interest, and the evolving energy R&D technologies being emphasized in the United States today, particular resources and technologies assume greater importance than others during the 50 year time period of interest considered in this fuels assessment. In particular, the size of the domestic coal resource base, the maturity of the coal extraction industry, the fact that coal gasification processes are on the verge of commercialization, the fact that large coal liquefaction demonstration plants are scheduled to be built during the next three years, and the aggressive efforts of ERDA in developing advanced coal conversion technologies all tend to indicate that coal's role in supplying energy to the United States will expand significantly between now and the end of the century. For similar reasons, much the same can be said of oil shale's future role in supplying energy.

Assessing the potential future contribution of the other carbonaceous resources is more difficult. Domestic tar sand resources, particularly in comparison to the other fossil resources, do not appear adequate to support a major synthetic fuels industry. Some technologies for generating energy from urban wastes have already been commercialized,

although the emphasis to date has been on either direct combustion for electric power generation or the conversion of wastes to liquid or gaseous fuel forms for local power generation.[28,29] There are still many unanswered questions relating to the ultimate role of energy crops.[30]

The discussion below gives an abbreviated overview of the production of the three jet fuel alternatives using coal and oil shale as energy sources. Also discussed is the production of hydrogen using nuclear power as an energy source, probably the most viable noncarbonaceous energy source from which hydrogen may be produced, at least throughout this century.

Synthetic JP Production

Synthetic JP from Coal. Synthetic JP production from coal has two major process steps: (1) coal liquefaction to produce a synthetic crude oil, and (2) the refining of that synthetic crude oil to jet fuel and other products. The liquefaction and refining facilities may be separate or integrated. The conversion of coal into a liquid basically entails reducing the carbon-to-hydrogen weight ratio, almost always by adding hydrogen. The hydrogen is usually derived from water (in the form of steam). The energy to generate the steam and to separate the hydrogen from water is most economically obtained from the coal itself.[31,32]

Some of the key parameters associated with the four major technologies for producing coal liquids are shown in Table 3. None of the technologies have yet been commercialized in the United States, although pilot plants using the first three technologies have been built or are scheduled to be completed before the end of this decade. In the comparative fuel evaluation presented later in this section, the direct hydrogenation H-Coal process is used as a representative coal liquefaction technology because it provides the largest yield of liquid products, provides a premium synthetic crude oil suitable for refining into jet fuels, and because it is a process that is receiving strong support from ERDA.

Table 3

COAL LIQUEFACTION TECHNOLOGIES

Process Type	Product Yields[a]	Process Pressures (Atmospheres)	Thermal Efficiencies	Process Names/Developers	Status
Carbonization/pyrolysis	.7-1.6 bbl 4000-9300 SCF	1-70	55-65	COED, FMC Corporation	36 T/D[b] pilot plant completed operations in November 1974
				COALCON, Coalcon Company	2600 T/D demonstration plant scheduled for operation by February 1979
Direct hydrogenation	2.5-3.2 bbl 2000-3000 SCF	136-272	60-75	H-Coal, Hydrocarbon Research Inc.	3 T/D plant operating, 600 T/D H-COAL pilot plant scheduled for operation by July 1978
				SYNTHOIL, Bureau of Mines	.5 T/D SYNTHOIL unit operating, 10 T/D pilot plant scheduled for operation by July 1977
Extraction	2-3 bbl 3500-4500 SCF	20 (extraction) 285 (hydrocracking)	60-70	SRC, Pittsburgh & Midway Mining Company	50 T/D pilot plant operating since September 1974, 6 T/D plant also operating
				CSF, Consolidation Coal Company	25 T/D plant shutdown in 1970, reactivated in 1974
Fischer-Tropsch	1.5-2 bbl	17-30	40-70	SASOL, South African Coal, Oil, Gas	5000 bbl/day commercial plant operating in South Africa

SOURCE: Refs. 29, 31-33.

[a]Yields in barrels of liquids and standard cubic feet of gases per ton of moisture-free and ash-free coal.

[b]Tons of coal input per day.

The technology for refining crude oils into a spectrum of products is highly advanced in the United States. Major oil companies in cooperation with ERDA, NASA, the Navy, and the Air Force are now attempting to determine through analytical procedures and experimental tests the unique process requirements for refining coal syncrudes into military fuels. Early work by the Sun Oil Company[34] and the Atlantic Richfield Company (ARCO)[35] is now being extended by the Exxon Research and Engineering Company under contract to the Air Force Aero-Propulsion Laboratory to assess the feasibility and process requirements for producing jet fuels from coal-derived crude oils. Following an experimental phase, material, equipment, and processing requirements will be assessed overall, as will the potential increase in jet fuel availability as a function of broadened specifications.[36]

The results of these studies indicate that the distillation of coal syncrudes produces more material in the kerosene (narrow-cut jet fuel) boiling range than is the case with typical natural crude oils (Table 4). This is a favorable result, since the major proportion of DoD liquid-fuel consumption is in the form of jet fuel. This could assume even greater importance in the future as the Air Force changes from wide-cut, naphtha-based JP-4 to narrow-cut JP-8.

Table 4

DISTILLATION YIELDS OF CRUDE OIL AND COAL SYNCRUDE

	Distillation Yields (volume percent)		
Boiling Range (°F)	East Texas Crude	H-Coal Syncrude[a]	COED Syncrude[a]
C^5-400 (gasoline)	40	37	33
400-515 (kerosene)	14	26	27
525-650 (heating oil)	12	17	24
650-975 (fuel oil)	20	20	16
975+	14	--	--
	100	100	100

SOURCE: Refs. 31 and 35.

[a]Derived from Illinois No. 6 coal.

Nevertheless, virtually all of the laboratory experiments to date suggest that straight-run distillation of synthetic coal crudes will not produce a product that can meet current jet fuel specifications, but rather results in a product high in aromatic content and deficient in hydrogen. This high aromatic content can create hot spots and burn-throughs in jet engine combustors, generate excessive smoke and infrared signatures, raise fuel freezing points, and accelerate the wear of engine seals.[5,37,38] However, these same laboratory experiments indicate that high-pressure hydrotreating (1000 to 3000 psi), which is not uncommon in today's refineries, can reduce the aromatic content to a few percent, resulting in a fuel product that can meet most of current jet fuel specifications. The experiments also suggest that the amount of processing required can be a strong function of the coal and liquefaction process used. For instance, the ARCO results indicate that middle distillate fractions of syncrudes from western coals have less than one-half the aromatic content of midwestern coals, which could have an important bearing on refining costs.

In summary, current evidence suggests that coal syncrudes can be refined into jet fuels that meet most of current narrow-cut jet fuel specifications, given some hydrotreating of the kerosene fraction. (The analysis in the next section assumes a refinery with both hydrotreating facilities and hydrocracking facilities to maximize jet fuel production.) The optimum tradeoff between hydrotreatment at the refinery and new or modified engine designs to cope with off-specification fuels has not yet been determined. It is not yet apparent whether coal syncrude refineries will initially be dedicated facilities or whether a more economic strategy will be to blend coal syncrudes with existing natural crude oils before refining.

Synthetic JP from Oil Shale. Synthetic JP production from oil shale involves (1) a retorting process in which the shale is crushed and heated to release the crude shale oil product from the shale, and (2) the refining of the crude shale oil into synthetic JP and other products. The oil shale may be mined and processed in a surface retort or processed *in situ* and pumped to the surface.

The three major processes closest to commercialization are the PARAHO process, the TOSCO-II process, and the Union Oil process--all developed largely by private sector R&D. ERDA and Occidental Petroleum are concentrating on the *in situ* techniques, which may allow the recovery of oil from shale deposits that are not readily recoverable using conventional mining techniques and at the same time reduce the problems posed by spent shale disposal.[29,39,40]

Crude shale oils derived from major domestic deposits in Colorado have been refined in laboratories and in a conventional crude-oil refinery. The results of these tests indicate that it is both feasible and practical to refine crude shale oil into military fuels meeting most product specifications. The largest program to date was sponsored by the Navy Energy and Natural Resources R&D Office in which 10,000 barrels of crude shale oil were refined in a conventional crude-oil refinery.[39]

The refined fuels, including JP-4, JP-5, and JET-A, while meeting most specifications, were found to be high in particulate matter and gum content and exhibited poor storage and thermal stability. However, in the judgment of the investigators, these problems were probably a consequence of the particular refinery setup and could be ameliorated by higher pressure hydrogenation (2000 to 3000 psi) and clay treatment. The refined fuels were delivered to a number of government laboratories, including the Air Force Aero-Propulsion Laboratory, for test and evaluation. After further treatment, the JP-4 was successfully used on a routine T-39 flight.[39]

The other major refining experiment now currently under way is Exxon's refining of coal syncrudes and shale syncrudes into jet fuels for the Air Force Aero-Propulsion Laboratory. Exxon is refining barrel-quantity samples from the PARAHO, TOSCO, and Occidental processes. Preliminary results reported by Exxon indicate that most specifications for JET-A and JP-4 can be met. All of the fuel blends produced in Exxon's laboratory setup using normal severity hydrotreatment had satisfactory thermal stability. Exxon has also observed that only the TOSCO shale-oil product provides a reasonable yield of wide-cut, JP-4-type jet fuel. They attribute this to the fact that many of the development

facilities use the light condensable liquids and gases as fuel within the processes. They also attribute the small quantity of wide-cut material to the high altitude of the facilities, which causes the product to lose its more volatile components in the heated storage tanks.[36] Whether this will continue to be the case with full-scale commercial facilities is an open question.

In summary, results indicate that shale oils can be refined to meet most or all of current jet fuel specifications and also that they can probably be refined in existing crude-oil refineries with only modest adjustments to those facilities. Whether economics will ultimately dictate that shale oils be refined to current specifications or that future engines be designed to operate on a broader range of fuels has yet to be determined.

Liquid Methane from Coal

The production of liquid methane from coal involves (1) a gasification process that can occur above ground or *in situ* to convert the coal into a raw synthesis gas, (2) a methanation step to upgrade the methane content of the gas, and (3) a liquefaction process to cool the gas to its liquid state of -249°F.

Characteristics of the major surface coal gasification techniques are noted in Table 5. Present utility and pipeline company planning indicates that the Lurgi process will probably constitute the backbone of any initial commercial-scale coal gasification industry in the United States.[29,33] ERDA has recently awarded phase I (design phase) contracts to two contractors for demonstration size facilities that will process from 2000 to 7300 tons per day of coal using a slagging Lurgi process and the COGAS process (coal-oil-gas, a variation of the COED coal liquefaction process). The entire demonstration program is scheduled to be completed by 1984. Because present planning suggests that some version of the Lurgi process is likely to be one of the first coal gasification technologies commercialized domestically, the comparative fuels evaluation presented later in this section assumes Lurgi technology is employed to produce gaseous methane.[29,33]

Table 5

MAJOR COAL GASIFICATION PROCESSES

Process	Gasifier Bed Design	Pressure (Atmospheres)	Temperatures (°F)	Gasifying Medium	Residue	Developer	Status
Lurgi	Fixed	30	900-2000	Steam, oxygen	Ash	American Lurgi	Commercialized in 1936
Koppers-Totzek	Entrained	1	2000-3300	Steam, oxygen	Slag	Koppers Company	Commercialized in 1952
Winkler	Fluidized	1	1350-1850	Steam, oxygen	Ash	Davy International	Commercialized in 1926
Bi-Gas	Entrained	68-102	1700-3000	Steam, oxygen	Slag	Bituminous Coal Research, Inc.	120 T/D[a] pilot plant scheduled for operation by June 1976
HYGAS®	Fluidized	68	1000-1850	Steam, oxygen, hydrogen	Ash	Institute of Gas Technology	75 T/D pilot plant operating since October 1971
Synthane	Fluidized	68	800-1800	Steam, oxygen	?	Bureau of Mines	72 T/D pilot plant scheduled for operation by May 1976
CO_2 Acceptor	Fluidized	10-20	1500-1900	Steam, air, dolomite	Ash	Consolidation Coal Company	40 T/D pilot plant operating since October 1972

SOURCE: Refs. 29, 33, 41-43.

[a]Tons of coal input per day.

Once coal has been gasified and the resulting synthesis gas methanated, it can be introduced into conventional high-pressure pipelines for distribution to a methane liquefaction plant that would normally be located near an air base to minimize the problems of distributing large quantities of cryogenic methane.

The technology for the liquefaction of natural gas on a large commercial scale is well established, with major plants being located in Algeria, Libya, Borneo, the USSR, and Alaska.[44] The basic liquefaction process consists first of purifying the gaseous methane, to ensure that no hydration or solidification of impurities occurs to block passages in the liquefaction heat exchangers. Typically, the gas is then cooled through a heat exchange process to a temperature of -259°F. The liquid methane is then stored in insulated tanks for later use.[45]

Large methane liquefaction complexes typically derive their electrical energy for compression equipment from the gaseous methane entering the complex. These fuel expenditures, together with losses, account for about 17 percent of the gaseous methane entering the liquefaction plant.[45]

In summary, technologies commercially proven, albeit in other countries, or new technologies under development in this country, could be used to convert coal to a liquid methane fuel suitable for aircraft applications.

Liquid Hydrogen Production

The production of liquid hydrogen considered here involves (1) obtaining gaseous hydrogen via coal gasification or water-splitting processes, (2) a possible purification of the gaseous product, (3) the liquefaction of the gaseous hydrogen, and (4) an ortho to para energy conversion of the liquid hydrogen that renders it suitable for storage.

The traditional method of producing gaseous hydrogen from coal consists of reacting coal with steam and oxygen to form a synthesis gas. A subsequent water gas shift reaction and removal of the carbon dioxide and residual carbon monoxide result in a gas rich in hydrogen.[43,46]

Although the current emphasis in the United States is on the development and commercialization of high-Btu coal gasification processes, these same processes already described could be used with some modifications to produce gaseous hydrogen. The modifications would include a requirement for water gas shift equipment to increase the hydrogen and carbon monoxide content of the synthesis gas at the expense of methane production.[46] The analysis of the three fuel alternatives as derived from coal, to be presented in a succeeding subsection, presumes that the above modifications are made to a Lurgi high-Btu coal gasification plant to enable it to produce a gaseous hydrogen product. A less traditional second-generation approach is being explored by the Institute of Gas Technology under ERDA sponsorship, in which hydrogen is produced by the decomposition of steam by iron oxide. A small pilot plant was scheduled to begin operating during the last quarter of 1976 to demonstrate the feasibility of producing hydrogen for HYGAS® high-Btu coal gasifiers using the steam-iron approach.[43,47,48]

Gaseous hydrogen can also be produced using nonfossil resources by splitting water molecules electrolytically, thermally, or thermochemically. Water electrolysis is a simple, clean, proven technology for generating hydrogen. Numerous analyses have shown that the large electricity requirements of the process result in electrolytic hydrogen costs two to three times as much as hydrogen produced from coal. Understandably, then, there is much interest in developing alternative water-splitting schemes to reduce energy requirements and costs.[49-52]

Because of the enormous technical problems associated with producing hydrogen by the direct thermal decomposition of water, researchers have begun investigating the feasibility of thermally decomposing water by a sequential operation of multistep chemical reactions.[53,54] Preliminary laboratory investigation of this technique indicates that it might theoretically approach the efficiency of coal gasification processes sometime in the future.[50] Hence, while it is now in a primitive state of development, thermochemical water-splitting may represent a long-term nonfossil-based option for producing hydrogen.

Whether the gaseous hydrogen is produced from coal or by water-splitting techniques using nuclear energy, it must be purified and

liquefied and must undergo an ortho to para energy conversion to render it suitable for storage and eventual use in an aircraft; otherwise, as much as 70 percent of the liquid product could be lost due to boil-off. The basic technology for liquefying hydrogen on a large scale was developed in support of the U.S. space program; the largest commercially built and operated plant has a capacity of 60 tons per day of liquid hydrogen. However, the scale of production would have to be significantly increased to support aviation applications; about 2500 tons per day might be required to support a large airport or air base.[55,56]

Hydrogen liquefaction is an extremely energy-intensive process, requiring large amounts of electric power to drive the compression equipment used in liquefaction. A recent and comprehensive study of hydrogen liquefaction by the Linde Division of Union Carbide indicates that a large liquefaction facility would consume 5.67 kWh(e) for every pound of hydrogen liquefied.[55] At current thermal to electrical conversion efficiencies, the thermal energy required to generate the electricity to liquefy the hydrogen exceeds the energy content of the hydrogen itself. For this reason, unlike methane liquefaction facilities, hydrogen liquefaction plants typically do not use gaseous hydrogen as a source of energy for power generation but rather use purchased electric power generated offsite.

Linde estimates that with equipment improvements, employing only a partial ortho to para energy conversion (requiring that consumption occur within 50 hours after liquefaction) and improved tail gas recovery, the electric power requirement could be reduced by 19 percent in the post-1985 time period. They also estimate that tail gas recovery and reductions in leakage could halve gaseous hydrogen losses in the liquefaction process.[55] However, even with these improvements, the hydrogen liquefaction process would remain very energy-intensive, with costs being very sensitive to the cost of the electric power.

OBSERVATIONS

We have surveyed major domestic energy resource alternatives to crude oil and natural gas that might be used in the synthesis

of military jet fuels in the future, the characteristics of the most attractive alternatives, and some of the production processes by which the fuels might be obtained. This survey indicates that jet fuels derived from oil shale and coal have the potential for beginning to make a contribution to jet fuel supplies between now and the end of the century because of the size of the resource bases and the pace of development of fuel conversion technology for these resources. The comparatively small size of the U.S. bituminous tar sand resource base and the lack of aggressive efforts to exploit this resource make it unlikely that tar sands will be a major energy source for jet fuels. The current technology emphasis for exploiting organic energy sources is not directed toward producing synthetic liquids suitable for jet fuel production but rather toward solutions to urban waste problems, in the process generating useful energy (primarily electricity) for local consumption.

Liquid hydrogen appears to be the only jet fuel readily producible from noncarbonaceous energy resources, primarily through the use of heat and/or electricity for water-splitting. However, these processes are markedly less economic than producing hydrogen from coal, both in an energy sense and in a cost sense. For this reason, it seems highly unlikely that any initial liquid hydrogen jet fuel industry in the United States would rely on an energy resource other than coal.

Thus, a pragmatic view of the resources and technologies involved, subject to change as the long-term technologies develop, is that at least between now and the end of the century, coal and oil shale are the most attractive domestic energy resource alternatives to crude oil and natural gas for the production of synthetic JP, liquid methane, or liquid hydrogen. Since development of fuel conversion technology for oil shale is focusing on the production of distillate products, such as synthetic JP-type fuels, a comparison of synthetic JP derived from oil shale and coal is subsequently examined in Sec. IV.

COMPARISON OF JET FUEL ALTERNATIVES DERIVED FROM COAL

To compare the three jet fuel alternatives on a consistent basis, the individual energy conversion facilities employing the technologies

already described were assembled into representative fuel supply systems with specific coal resource supply locations and fuel consumption points (Fig. 24). The previously described assessment of resources, plus material in the appendix, provided the necessary information to locate major coal deposits, while a representative, yet manageable, basing scheme was adapted from a related applications analysis of very large airplanes.[8] The fuels are first compared in terms of the energy requirements for their production and distribution.

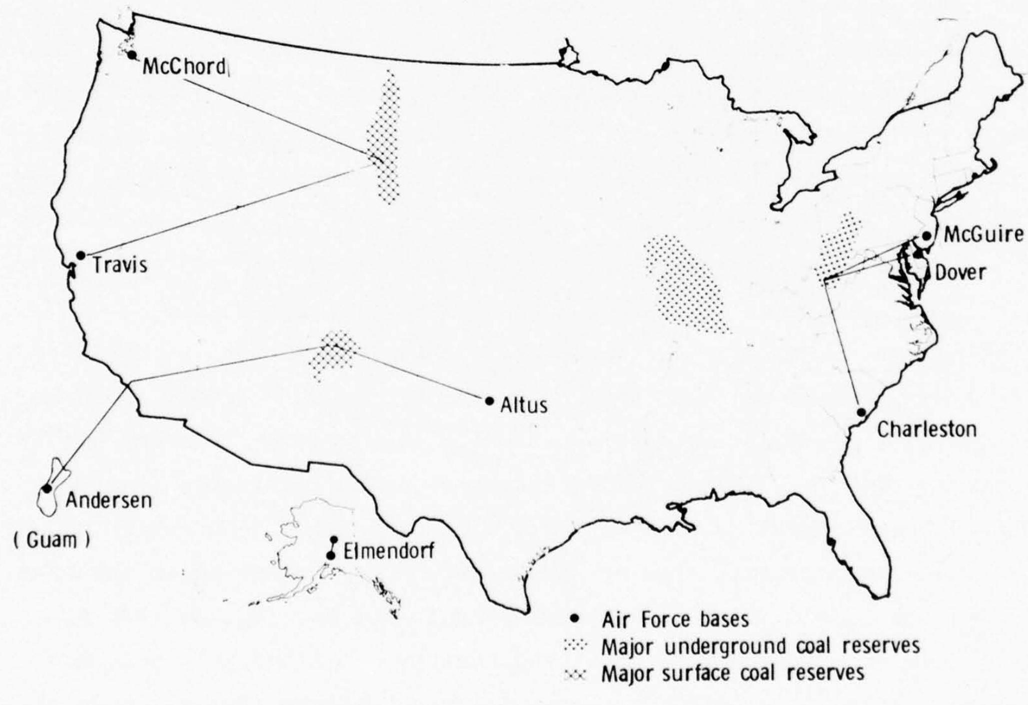

Fig. 24 — Fuel supply paths

Energy Requirements for Fuel Production

Consideration of the energy expenditures required for fuel production is motivated by several factors. An understanding of the technical reasons why certain fuel production processes are more energy-intensive than others can lead to a greater understanding of the reasons why fuel alternatives differ in cost. Consideration of the energy required to produce and distribute a fuel also permits a complete assessment

of the total energy intensiveness of a given aircraft-fuel alternative, including not just the fuel burned on board an aircraft, but also the energy required to convert the fuel to a form suitable for use in an aircraft. Finally, it seemed prudent to identify the total energy requirements that particular fuel alternatives would impose on the nation's energy resource base, since the Air Force will be competing for these energy supplies with many other users in the marketplace.

Figure 25 shows the major components of representative fuel supply systems being developed from a variety of sources.[11,28,31,43,45,46,55-60] Let us focus first on the details of the liquid hydrogen supply system. Typically, surface-mined western coal could be transported from the mine a short distance (about ten miles, for example) via a diesel train to a coal gasification plant that uses Lurgi technology, where the coal would be gasified, shifted, and purified to hydrogen. The long-haul distribution leg would consist of a high-pressure pipeline to a liquefaction facility near the air base. The example shown is equivalent to pipelining the gaseous hydrogen from the Wyoming Powder River Basin to the West Coast of the United States, a distance of about 900 miles. The gaseous hydrogen would then be converted to a liquid state, would undergo the ortho to para conversion, and would then be stored in cryogenic tanks for ultimate distribution to an aircraft fueling manifold via a short liquid hydrogen pipeline about two miles in length.

In Fig. 25, the numbers enclosed by dashed lines trace the flow of resource energy (energy derived from the primary energy resource--coal) from extraction to ultimate distribution. In this example, 289 Btu of coal are required to deliver 100 Btu of hydrogen and 35 Btu of by-products. Of course, other energy must also be expended to fuel the diesel train, build the facilities, generate the electricity required for liquefaction, etc. This energy, termed process energy, is shown below the elements of the fuel supply system. Of primary interest is the large process energy expenditure associated with hydrogen liquefaction and the ortho to para conversion, which is roughly equivalent to the resource energy content of the gaseous hydrogen entering the facility. As a consequence of this expenditure, about 3.2 Btu of energy must be input for every Btu of liquid hydrogen and by-products output.

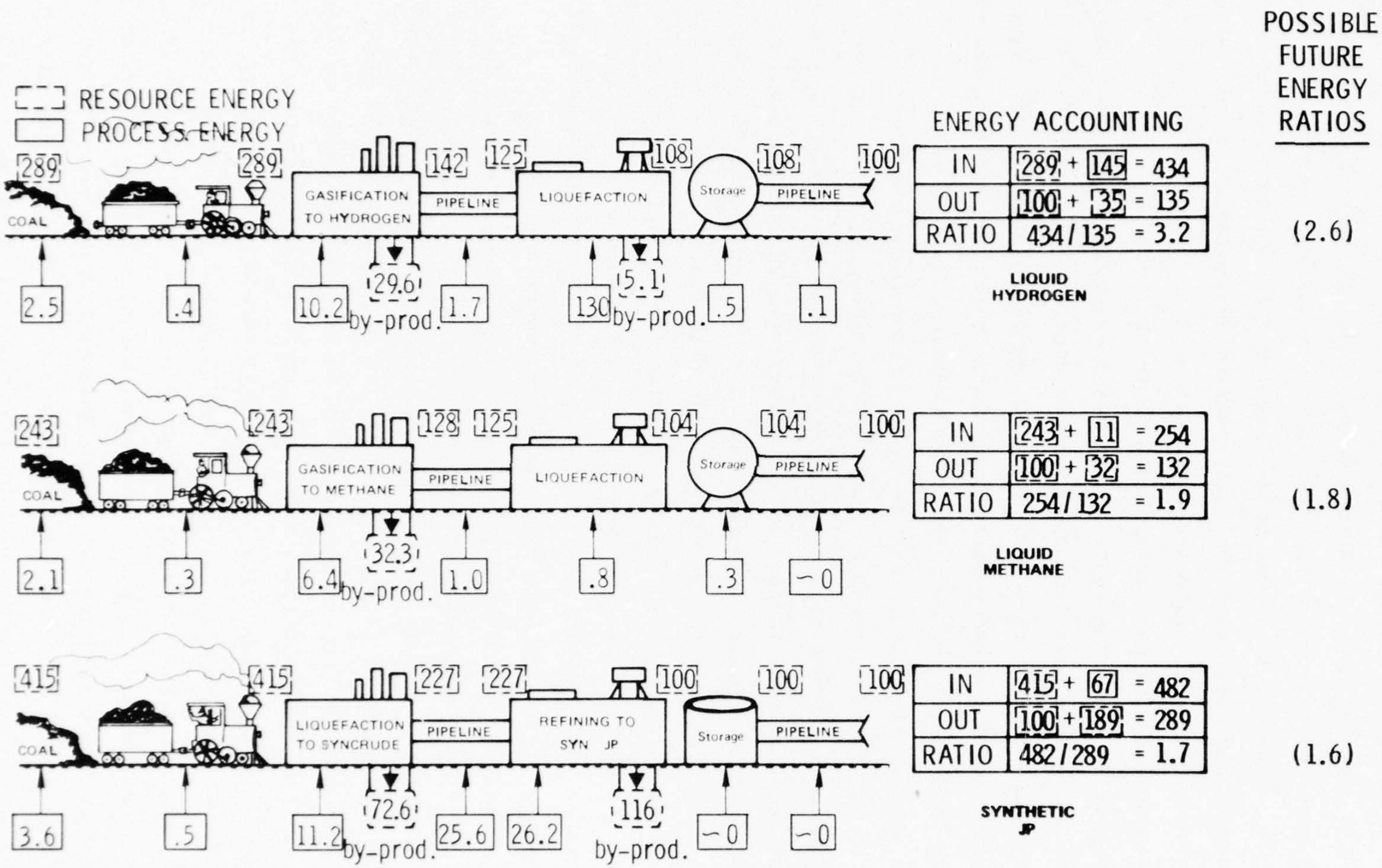

Fig. 25 — Energy flow for synthetic fuels

Thus, the liquid hydrogen supply process is significantly more energy-intensive than today's crude-oil supply system, which requires about 1.2 Btu of energy input for every Btu of refined products output.*

The components of the liquid methane system are essentially analogous to the liquid hydrogen system. A Lurgi gasifier is also used in the liquid methane supply system, but in this case the product gas undergoes a methanation reaction which results in a pipeline quality gas which is high in methane. The liquid methane supply process requires less energy than the liquid hydrogen process, primarily because methane liquefaction requires only about 10 to 15 percent of the electric power required for hydrogen liquefaction.(43) In this instance, the literature suggests that typically, part of the gaseous methane is used to generate the electricity for liquefaction because the scale of electricity required is sufficiently low as to not preclude on-site power generation.(28,43,45) With resource energy (the gaseous methane) supplying the energy for electric power generation, the process energy shown in Fig. 25 for methane liquefaction accordingly reflects only the energy required to build the facility. The methane supply process also requires less energy than the hydrogen process because pipelining gaseous methane requires only about 20 to 25 percent of the pumping energy required when pumping gaseous hydrogen. This is in part due to the lower volumetric heating value of hydrogen (275 Btu per standard cubic foot versus 912 Btu per standard cubic foot for methane).(21) The energy accounting shows that 1.9 Btu of energy must be input for every Btu of liquid methane and by-products output.

For the synthetic JP supply system, more coal is required than for the other two alternatives. This is because it is estimated that less than one-half of every barrel of syncrude produced by the H-Coal high-pressure hydrogenation process could be refined to yield a kerosene-like jet fuel; the bulk of the remainder constituting unleaded motor

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*All of the energy values cited in the comparison are net or low heating values, in which the heat of condensation of water is not included. This is appropriate for controlled combustion systems such as aircraft engines, in which the combustion products are discharged as a gas.

gasoline, which should find a ready market around the year 2000.[31] Thus the greater coal requirement is a direct reflection of the greater amount of energy being delivered. The comparatively large process energy required for syncrude refining is also significant. This is a consequence of the hydroprocessing that the coal syncrude must undergo, primarily because of the characteristically high aromatic content of coal syncrude liquids. In the example shown, the syncrude refinery is structured to maximize the output of jet fuel by hydrocracking the heavier distillate fractions to jet fuel and lighter products, primarily gasoline. If a lower yield of jet fuel were acceptable, the energy requirements could be reduced. The energy accounting shows that the synthetic JP supply process requires that 1.7 Btu of energy be input for every Btu of synthetic JP and by-products output.

The energy expenditures shown in Fig. 25 are largely characteristic of current or short-term technology. The energy ratios shown on the far right might result if some postulated improvements in the fuel supply systems were to occur in the future. As might be expected, because the hydrogen supply process is highly energy-intensive, it profits the most from possible improvements in technology. In developing possible future energy ratios, it was assumed that hydrogen gasification efficiency might be increased to 70 percent with the introduction of advanced second-generation equipment. A modest 4 percent reduction in pumping energy required for the gaseous hydrogen pipeline is assumed. The most significant improvement would be due to better thermal to electrical conversion efficiencies--from the 33 percent efficiencies of today to an optimistic 50 percent in the future. It is further assumed that the improvements in the hydrogen liquefaction process discussed earlier could be implemented, with the exception of the partial ortho to para energy conversion requiring consumption within 50 hours of production. This does not seem viable from an Air Force perspective, because of the uncertainty of needing to draw large quantities of fuel out of storage for contingency situations on an irregular basis. Additionally, analyses of hydrogen storage requirements, which considered the reliability of the individual units of the liquid hydrogen supply process, have indicated that a storage capacity equivalent to 4 to 13

days of daily production could be required to assure a continuous supply of liquid hydrogen during subsystem module production outages.[56] In developing the future energy ratio, it was further assumed that the loss of liquid hydrogen in pipelining it to the aircraft fueling manifold might be halved if extensive efforts were made to recover vaporized fuel. This is a particularly optimistic assumption, since NASA experience with handling liquid hydrogen for space applications indicates that only about two-thirds of the liquid hydrogen delivered to the Kennedy Space Center is actually used in launch vehicles; the remainder is lost during tanker transfers, to boil-off during storage, and for fulfilling gaseous hydrogen requirements for purging tanks, etc.[61]

For the liquid methane supply process, it is also assumed that gasification efficiency improves to 70 percent, the gaseous pipeline energy requirements are reduced by 4 percent, and energy losses in the liquid methane pipeline are halved. For the synthetic JP process, it is assumed that the energy intensiveness of the syncrude pipeline is improved modestly. The rather severe energy requirement for the syncrude pipeline shown in Fig. 25 is based on the assumption that all of the pumping energy is derived from electric power. This assumption was more a result of lack of clear available information on other more efficient types of pipeline pumping than on any technological limitation on using other more efficient energy sources for pumping.[57]

The admittedly optimistic set of assumptions for future improvements in the liquid hydrogen supply process was deliberately assembled to test the hypothesis that liquid-hydrogen-fueled aircraft would be less energy-intensive in the future than the other alternatives. However, even with this rather optimistic outlook, a related Rand analysis indicates that for a large class of military missions, the lower onboard consumption of energy of a subsonic liquid hydrogen transport aircraft is more than offset by the large energy expenditures associated with the fuel production and distribution process.[8] Thus, while all of the synthetic fuel alternatives require larger energy expenditures than today's crude-oil supply process, the liquid hydrogen supply process appears to be dominantly more energy-intensive than the processes by which the other two coal-derived fuels are obtained.

Costs of Fuel Production

It is difficult to estimate in an absolute sense the costs of synthetic jet fuels produced from coal in the absence of any operating commercial facilities in the United States. However, by making consistent assumptions about coal costs, electricity costs, financing rules, distribution systems, consumption points, etc., insights can be gained into the relative costs of producing the three fuel alternatives. Such an approach is taken below in comparing the costs of producing the three fuel alternatives. The sensitivities of these fuel costs to alternative assumptions in the key parameters are then systematically explored.

Basic estimates of the delivered costs of the three fuel alternatives were developed for the fuel supply paths shown in Fig. 24, using technologies commensurate with those illustrated in Fig. 25. Underground-mined West Virginia bituminous coal constituted the energy source for East Coast air bases, while surface-mined western subbituminous coal drawn from the Four Corners region of New Mexico, the Wyoming Powder River Basin, and Alaska was assumed to be used for the other bases. The minemouth cost of the eastern coal was assumed to be $20 per ton and the western coal $5 per ton, the large cost difference primarily being due to the greater productivity possible in surface mining in comparison to undergound mining.[62] Of course, in making relative comparisons between the costs of the three fuels, consistency in assumed coal costs across the alternatives is more important than precise cost estimates. However, as of June 1974, utilities in the eastern United States were paying from about $17 to $23 per ton for coal from eastern underground mines, whereas utilities in the west were paying from $4 to $9 per ton for coal from western surface mines; hence, these assumed costs are within the range of costs characteristic of the 1974 time period.[63] Since then, coal costs have risen in some markets, with some short-term contracts for underground-mined coal exceeding $40 per ton. As a consequence, the sensitivity analysis will include the impact of higher coal costs on delivered fuel costs. Costs associated with the energy conversion facilities, adapted from source data, are noted in Table 6. These costs are also treated in a parametric fashion in the sensitivity analysis. The information in

Table 6

ENERGY CONVERSION FACILITY COSTS

(In 1974 dollars)[a]

Facility[b] (250 Billion Btu of Fuel Output per Stream Day)	Investment Cost[c] ($ millions)	Annual Operating Cost Excluding Energy[d] ($ millions)	Process Electricity Costs per Stream Day[e] ($)	Other Process Energy Costs per Stream Day[f] ($)
Coal gasification to hydrogen	648	44	--	--
Hydrogen liquefaction	631	27	394,000	--
Coal gasification to methane	432	39	--	--
Methane liquefaction	86	3	--	--
Coal liquefaction to syncrude	423	32	--	--
Syncrude refinery	123	7	4,430	47,340

SOURCES: Refs. 31, 45, 46, 55, and 60.

[a]Costs are those prevailing during the first half of 1974. Adjustments were made to source data using the Chemical Engineering Plant Cost Index.(64) The reader is cautioned that resource energy costs are not included. These costs vary according to coal costs, types of coal, efficiencies of the processes, and distribution distances, all of which are accounted for in Fig. 26.

[b]Technologies represented are those previously mentioned in the energy evaluation. The energy output of the facilities includes not just hydrogen, methane, and synthetic JP fuel products, but also other fuel by-products such as gasoline, LPG, low-Btu gas, naphthas, phenols, etc. The energy production of these facilities (250 billion Btu per stream day) is approximately equivalent to the energy content of 45,000 barrels of crude oil.

[c]Investment costs include a 28 percent ownership cost over and above basic facility investments to cover interest during construction, working capital, start-up capital, etc.

[d]Sulfur and ammonia by-products are credited against operating costs. Sulfur was valued at $25 per long ton, ammonia at $100 per long ton.

[e]Electricity valued at 15 mills per kWh. Four of the facilities use resource energy, either from coal or gaseous methane, for the generation of on-site electricity. A stream day is one day of plant operation at full capacity.

[f]Syncrude refinery requires supplemental plant fuel for hydrogen generation valued at $1.94 per million Btu.

Table 6 was integrated with distribution and storage cost information[21,56-58] to develop the cost estimates for the three fuels shown in Fig. 24.

The fuel costs shown in Fig. 26 represent the average cost in dollars per 1 million Btu of fuel energy to deliver each of the three fuel alternatives to the consumption points shown in Fig. 24. This measure of cost is used rather than the more traditional cost per gallon, because the vastly different volumetric heat contents of the three fuels make a cost per gallon comparison meaningless. However, as a benchmark, as of June 1976, the Air Force was paying the Defense Fuel Supply Center (DFSC) 42 cents per gallon for JP-4, which is equivalent to about $3.45 per million Btu.[65] The fuel costs reflect the mix of eastern and western coal, the mix costing 54 cents per million Btu, or $9.64 per ton.

Because the energy conversion facilities contribute significantly to the cost of the three fuels, the major cost categories have been identified according to the fixed (capital charges), operating (recurring labor costs, property taxes, raw materials, etc.), and energy costs for these facilities. As would be expected from an examination of Table 6, all of the energy conversion facilities are quite capital-intensive. These capital charges are a strong function of the method by which the plants are financed, which is explored in the sensitivity analysis. The energy flow analysis showed large electrical energy requirements for hydrogen liquefaction. This energy expenditure constitutes a major cost component of liquid hydrogen production, even for a comparatively modest electricity cost of 15 mills per kWh assumed in the computations. If credits are applied for the energy by-products, particularly for the large gasoline by-product, costs of $8.20, $3.56, and $2.91 per million Btu are obtained for the liquid hydrogen, liquid methane, and synthetic JP, respectively.* Thus, liquid hydrogen

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*Energy by-products, including the gasoline output of the syncrude refinery, were valued in proportion to their share of the energy output of each facility. Such an assumption might tend to slightly overstate the cost of the synthetic JP, since in the past, light refined products from crude-oil refineries, including gasoline, have commanded a higher price in the marketplace than the kerosene used for jet fuel production.

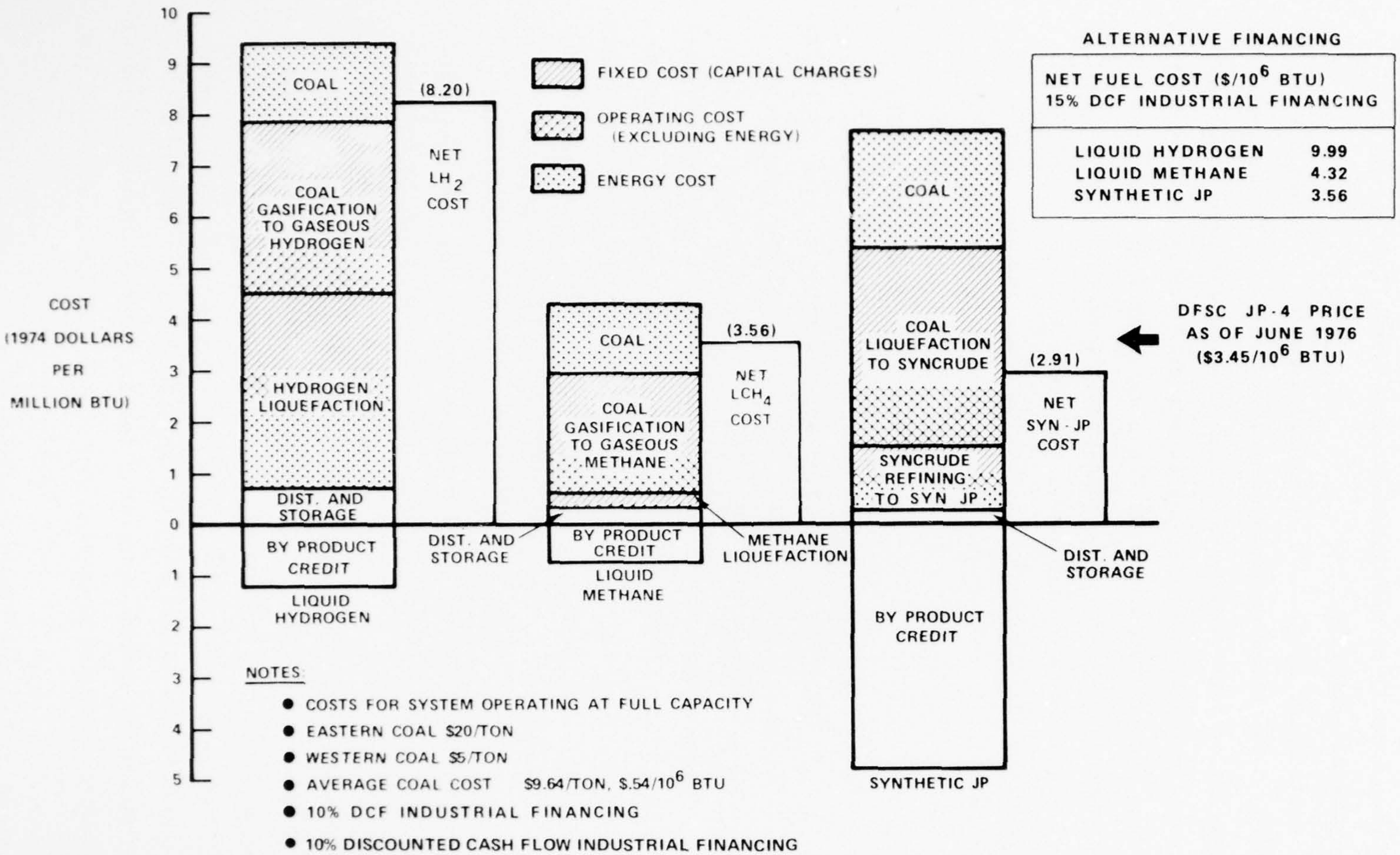

Fig. 26 — Fuel costs

production appears to be considerably more costly than production of the other two alternatives.

The costs noted above were developed assuming a 10 percent discounted cash flow return on investment after taxes.* It has been suggested that to attract private industry to enter synthetic fuel production as well as to generate the equity required for the rapid build-up of a synthetic fuels industry might require investment returns of 15 percent or more.[66] Under such conditions, fuel costs could easily reach the levels shown in the box in Fig. 26.

An important distinction should be made between the "cost" of a fuel and its "price." The costs shown on the bars in Fig. 26 represent the operator's cost plus a 10 percent return on investment; they do not necessarily reflect the price that the fuel would sell for on the open market. The coal syncrude cost associated with the synthetic JP production in the example is $11.33 per barrel. The cost of the refined synthetic JP is about 37 cents per gallon and the gasoline is about 33 cents per gallon (excluding state and federal taxes). These costs are roughly commensurate with current market prices for refined petroleum products. Thus, it seems apparent that synthetic fuels only begin to become competitive in the environment of the petroleum prices prevailing today. Of course, world oil prices reflect far more than cost plus a 10 percent return on investment. Since large quantitites of Middle East oil could be pumped to the surface and transported to the United States for about $1.50 a barrel plus profit, jet fuel could potentially be produced from imported crude oil at costs on the order of one-quarter to one-half those associated with the production of a coal-derived jet fuel.[24] Hence, private industry is presently unwilling to assume the risks of initiating a synthetic fuels industry, given the uncertainties in future world crude-oil prices.

The costs developed in Fig. 26 are subject to considerable uncertainty, depending on trends in coal costs, electricity costs, the method by which the energy conversion facilities are financed, possible growth in investment and operating costs, and the manner in which the

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*Sixteen year depreciation schedule, 30 year project life.

energy is delivered, among other factors. The sensitivity of the cost of the three fuel alternatives to these parameters is systematically explored in Fig. 27. It should be emphasized that while the costs developed in Fig. 26 were those associated with supplying a set of air bases, the parametric analysis uses a single air base for example purposes. The nominal baseline from which the excursions in cost were examined is shown in Fig. 27.

Figure 27 illustrates that coal cost is one of the major determinants of the cost of the three fuel candidates. It is also important to note that the liquid hydrogen supply process is more sensitive to coal costs than are the other two alternatives. This is a consequence of the fact that any increases in upstream costs (e.g., coal costs) more adversely affect the downstream costs (e.g., fuel costs) of those processes that are less efficient, and, hence, recover less of the more costly coal resource energy in the final fuel product.

The hydrogen production process is also more sensitive to unfavorable changes in the other parameters as well. This is clearly the case in Figs. 27(b) and (c). It is interesting to note that even with a doubling of the capital investment and operating costs (excluding energy) of the liquid methane and synthetic JP alternatives, the liquid hydrogen product is still considerably more costly. Liquid hydrogen costs are also very vulnerable to increases in electricity costs because of the large electric power requirements for liquefaction illustrated in Fig. 27(d).

By examining the slopes of the curves in Figs. 27(e) and (f), it is clear that it is more economical to locate coal liquefaction or gasification plants near the minemouth so that produce gases or liquids can be transported by more economic pipeline methods. However, the lack of water for coal conversion facilities in the arid western states, to be discussed subsequently, may require that the coal be transported by rail to areas where water is more abundant. This would tend to increase the delivered costs of each of the three fuel alternatives.

In addition to the more obvious effects of resource costs, capital costs, financing, etc., on synthetic fuel costs, the dramatic

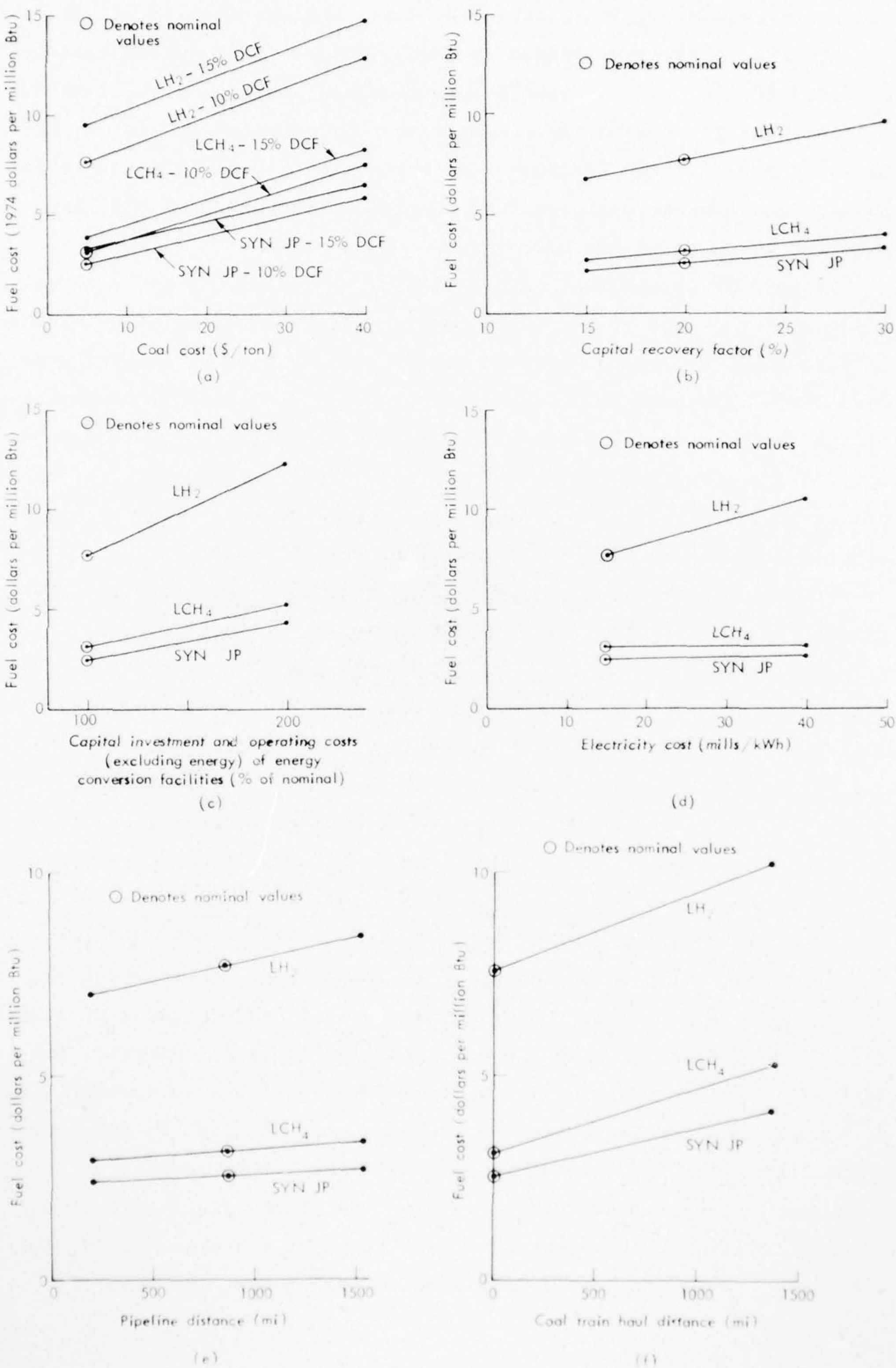

Fig. 27—Fuel cost sensitivities

differences in aviation fuel demands by the military during peacetime and wartime operations could have a pronounced effect on fuel costs. The costs shown in Fig. 26 are associated with a fuel system operating at full capacity, assuming all the fuel produced could find a market with the Air Force and other users. However, if a fuel supply system, sized to meet a contingency or wartime requirement, is underutilized during peacetime, Air Force synthetic fuel costs could rise. The results shown in Fig. 28 apply if there are no alternative markets for the excess liquid hydrogen, liquid methane, or refined syncrude products during peacetime. If such a situation prevailed, the liquefaction or refinery facility owner would have to cover his substantial fixed costs by charging a higher price for the lesser amount of liquid hydrogen, liquid methane, or synthetic JP being produced. We will consider a single air base example to illustrate this effect.

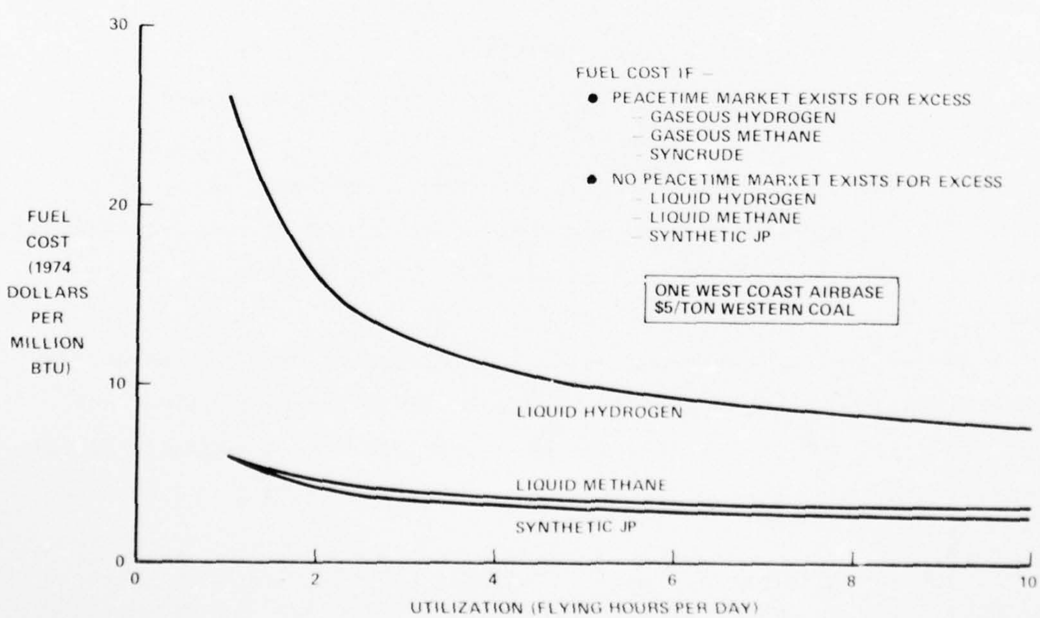

Fig. 28 — The effect on fuel costs of reduced aircraft use during peacetime

In Fig. 28, aircraft utilization rate is used as a measure of the use of a fuel supply system. The fuel supply system was sized to support transport aircraft that might fly 10 hours per day during a contingency situation. However, during peacetime such aircraft might fly only about 1.5 to 2.0 hours per day, about the same number of hours as the Air Force's C-5A heavy airlifter today. The cost of the liquid hydrogen could rise dramatically at such a low utilization rate. The cost increase associated with the other two fuel alternatives is not nearly as severe because of the lower capital intensiveness of the methane liquefaction plant and the coal syncrude refinery. Furthermore, for the synthetic JP alternative, it seems far more likely that the refined syncrude products would be assimilated during peacetime into existing petroleum markets by the turn of the century.*

Of course, the notion of complete reliance by the Air Force on just synthetic fuels is somewhat idealistic; and thus the potential supply of synthetic fuels and petroleum fuels in the future needs to be assessed in the context of competition for these fuels, and the extent to which competitors could use alternative fuels if Air Force requirements were to increase in a contingency. To cite an example, the commercial airlines might also be users of synthetic jet fuels. However, they might not qualify as interruptible users, since 17 percent of all long-range and 100 percent of all cargo or cargo-convertible aircraft might be used as part of the U.S. Civil Reserve Air Fleet during a major contingency situation.

We can summarize the analysis of fuel production costs by noting that liquid hydrogen appears to be considerably more expensive than the other two fuel alternatives. Of course, to make a complete assessment of the relative cost of the three fuel alternatives, we must

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*Another alternative would be to size the fuel system to more closely match peacetime fuel requirements and provide for the wartime requirement by maintaining large quantities of the fuels in storage. However, this would not completely ameliorate the problem of liquid hydrogen cost, particularly when the sophisticated and expensive storage of liquid hydrogen is compared to the cheaper storage available for liquid methane, and the comparatively unsophisticated storage needed for refined syncrude products (Refs. 56, 58).

consider the use of the fuels in aircraft. A related Rand mission analysis of large transport-class airplanes (e.g., gross weights of 1 to 2 million pounds) fueled by synthetic JP, liquid hydrogen, liquid methane, *or* nuclear propulsion has indicated that for a broad class of present and future mission applications, a synthetic-JP-fueled aircraft is significantly more cost effective than the other alternatives, for fuel costs in the range of those cited in Fig. 26. Nuclear propulsion begins to look attractive only for station-keeping missions that require large station radii (greater than 400 n mi) and extremely long loiter times on station (e.g., hundreds of hours). At present, no missions requiring such a capability are apparent.[8] Only major reductions in the costs of liquefying gaseous hydrogen would improve the relative attractiveness of liquid hydrogen.

Resource Availability

In addition to the cost and energy considerations associated with fuel production, resource issues must also be considered, such as the rate of coal production required to support a synthetic fuels industry and the long-term availability of coal under such rates of production. There is also the question of whether currently available water resources in the western United States would be adequate for the coal conversion facilities that might be located adjacent to large surface-mineable coal deposits.

The rate at which U.S. coal production might expand will depend to a substantial degree on the success or failure of competing energy technologies to lessen the nation's dependence on crude-oil imports. ERDA has developed six scenarios, indicated in Fig. 29, which cover a spectrum of possible paths of evolution for the U.S. energy system, each of which would require significant growth in U.S. coal production.[17] ERDA's results indicate that domestic coal production would have to expand at an average annual rate of more than 5 percent to accommodate the evolving coal needs of a synthetic fuels industry and demands by other users for coal. Other investigations suggest growth rates as high as 7 percent per year.[67] A 7 percent growth rate corresponds to a doubling of production capacity every 10 years.

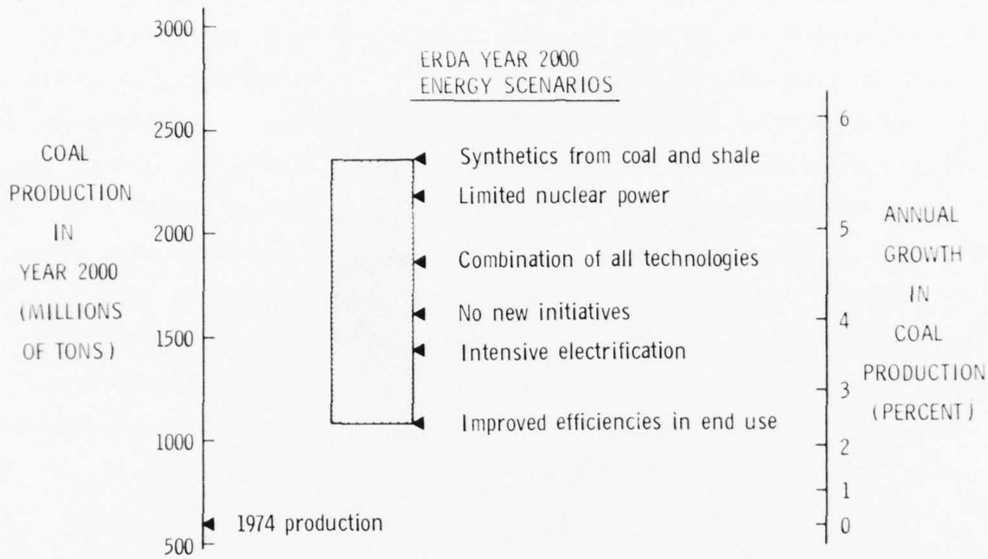

Fig. 29—Coal use in ERDA energy scenarios (from Ref. 17)

It has been suggested that this would require opening two new major coal mines each month for 10 years. This high growth rate can be contrasted with what happened during the 1960s, when only 13 new major coal mines were opened.[68]

This growth in coal production can be measured against estimates of currently economically recoverable domestic coal reserves to gain insights into coal's availability for the future. Shown in Fig. 30 is cumulative coal production by year for several annual growth rates, with the 5 to 7 percent growth rates highlighted. The National Petroleum Council (NPC) estimate shown includes only measured and indicated reserves above the depth of 1000 feet in thick seams.[62] The United States Bureau of Mines (USBM) further includes coal seams of intermediate thickness.[69] Complete information on the ERDA estimate is not available; however, it clearly includes some coal from the inferred reserves category as well as some coal from the unmapped and unexplored category.[17]

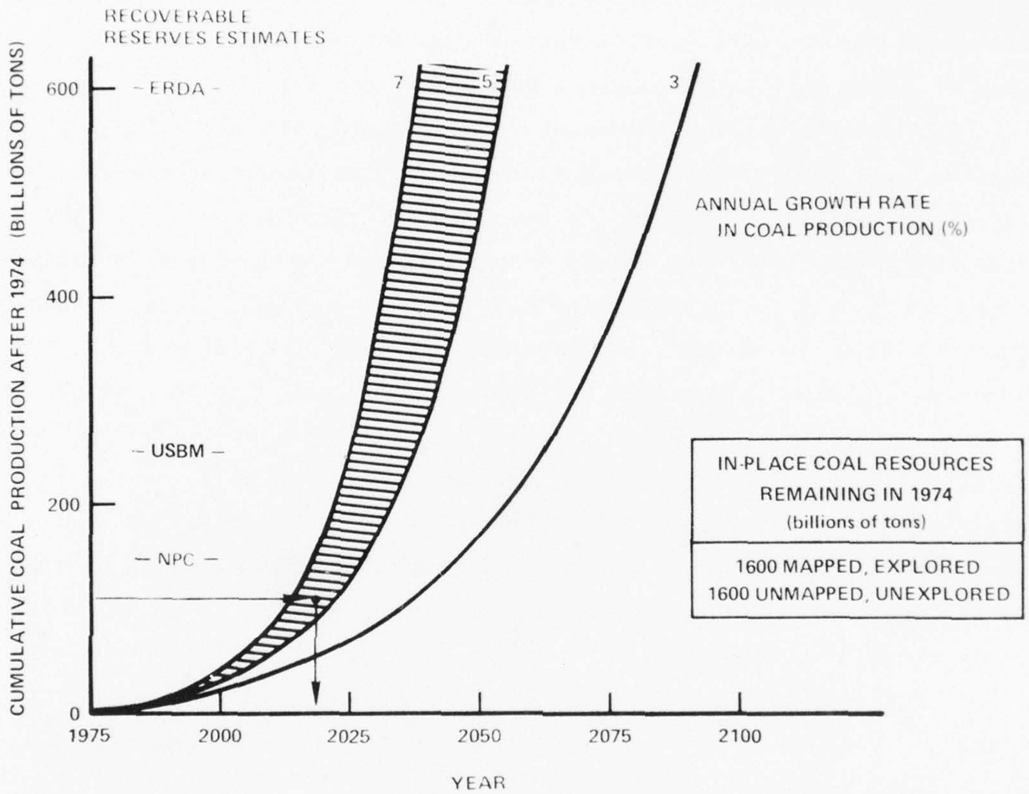

Fig. 30 — Coal resource depletion trends
(from Refs. 17, 62, 67, and 69)

In interpreting Fig. 30, an analogy may be made to the current problems being experienced with domestic petroleum production. Price and availability problems really began shortly after domestic production peaked, forcing users to search for alternative sources of energy--in this case imported petroleum. In the case of coal, note that one-half of the currently economically recoverable reserves might be depleted during the first or second quarter of the next century if the high growth rates suggested were to be sustained. Thus, the size of the resource base is adequate to supply an increasing fraction of U.S. energy needs into the next century even at the high growth rate. Further

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THE POTENTIAL ROLE OF TECHNOLOGICAL MODIFICATIONS AND ALTERNATI--ETC(U)

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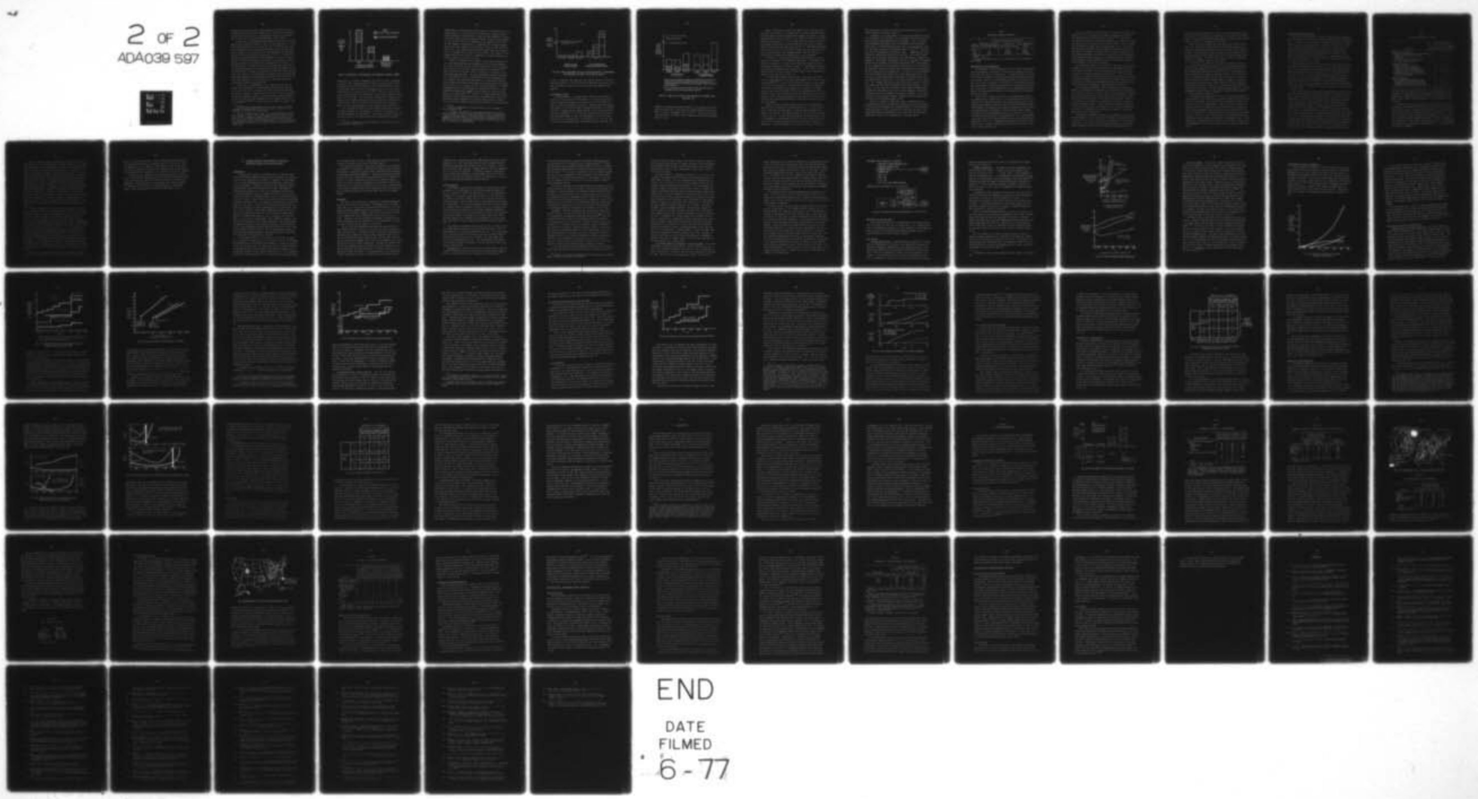

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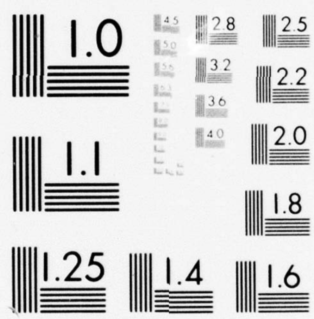

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

mapping and exploration should further expand the definition of the economically recoverable coal resource base. Of course, environmental and other factors will exert a restraining influence on coal growth, some of which will be discussed subsequently in this section.

The specific coal requirements for producing the three fuel alternatives have already been shown in Fig. 25 on an energy basis. If the Air Force had derived all of its jet fuel for FY 1975 from coal, the coal requirements for the liquid methane option would have been equivalent to about 9 to 12 percent of U.S. coal production, liquid hydrogen from 11 to 15 percent, and synthetic JP from 15 to 21 percent, depending on whether bituminous or subbituminous coal were the energy source.* Recalling the energy flow analysis, the synthetic JP option requires the most coal because of the large gasoline by-product. If the electricity for hydrogen liquefaction were generated using coal, the liquid hydrogen option would require about the same amount of coal as the synthetic JP option yet would deliver about half as much energy. While these annual coal requirements for synthetic jet fuel production seem large compared to current production levels, none of the alternatives would deplete even 0.1 percent of the currently economically recoverable reserves in any given year.

In addition to consideration of coal production capacity, the ability and likelihood of a coal synthetic fuels industry meeting the jet fuel needs of the military and other users by the year 2000 must also be assessed. Shown on the left of Fig. 31 are two estimates† of what the potential synthetic jet fuel production capacity might be by the year 2000, with the uncertainty in the ultimate yield of jet fuel highlighted.[17,62] To put these two estimates of capacity into

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*Assuming that subbituminous coal has a heat value of 7800 Btu per pound, bituminous coal 10,820 Btu per pound, and domestic coal production of 600 million tons per year.

†The NPC estimate shown in Fig. 31 is an extrapolation of their 1985 estimate. In both cases, resulting synthetic jet fuel outputs were calculated using coal inputs estimated by NPC and ERDA, and the synthetic JP fuel supply process energy expenditures shown in Fig. 25. Information in Fig. 31 is derived from Refs. 21, 62, and personal communication from William Vance, Defense Energy Information Service, October 1975.

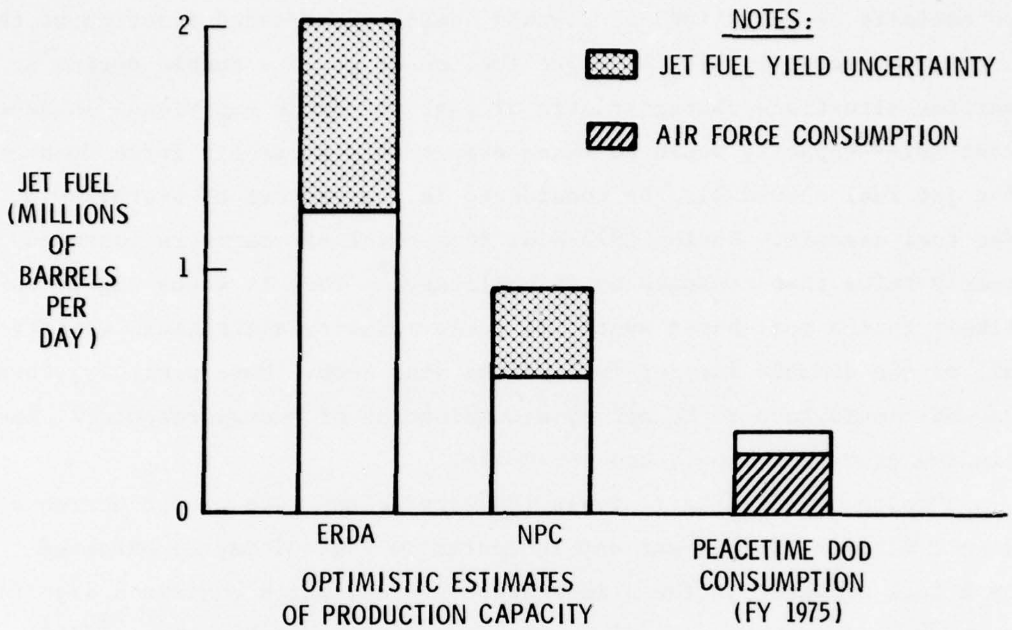

Fig. 31 — Projections of coal-based jet fuel production capacity in 2000

perspective, the Synfuels Interagency Task Force recently recommended a synthetic fuels commercialization program to the President's Energy Resources Council that would result in only 50,000 barrels per day of coal syncrude liquids by 1985, 20,000 barrels per day of which might optimistically be refined to jet fuel.(66) Clearly, to reach the production levels projected by ERDA and NPC would require a major build-up between 1985 and 2000. This conclusion is essentially unchanged when projections of high-Btu coal gasification capacity are considered, the closest analogy that can be made to the gasification facilities required for the liquid methane or liquid hydrogen supply processes.

These estimates of capacity can be compared with overall DoD and Air Force peacetime jet fuel demands, the Air Force accounting for over three-quarters of that demand.* If the more conservative NPC projection is used, we note that while military peacetime needs might

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*Personal communication from William Vance, Defense Energy Information Service, October 1975.

potentially be satisfied, they would constitute a large fraction of the overall market. If Air Force jet fuel needs were to double during a wartime situation--characteristic of past Air Force experience in Southeast Asia--capacity would be taxed even more. These Air Force demands for jet fuel should also be considered in the context of overall U.S. jet fuel demands. During 1975 U.S. commercial air carriers consumed nearly twice that consumed by the military.* Thus it seems highly unlikely that a coal-based synthetic fuels industry alone could satisfy all of the demands for jet fuel in the year 2000. More probably, those demands would have to be met by a combination of energy resources, including crude oil, coal, and oil shale.

Growth of a synthetic fuels industry to the rate of production of 1 to 2 million barrels per day indicated in Fig. 31 may be hindered by a lack of water in the arid western states, which contain a significant fraction of the nation's surface-mineable coal deposits.[(70,71)] Recall that water is a major source of hydrogen in coal gasification and liquefaction processes. The water availability problem is graphically illustrated in Fig. 32, which shows the water requirements for the synthetic fuel facilities postulated to be located near abundant coal reserves in New Mexico and Wyoming to serve the western air bases shown in Fig. 24.† Also shown are the water requirements for the NPC's postulated New Mexico and Wyoming coal conversion facilities. A coal liquefaction plant could consume over six barrels of water for every barrel of syncrude output.[(31)] However, the liquefaction plant is not inherently any more water intensive than the gasification facilities; the greater water requirement reflects the larger amount of energy that is delivered because of the gasoline by-product. The results shown

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*Personal communication from Evans Whiley, Civil Aeronautics Board, November 1975.

†The annual coal inputs for these energy conversion facilities sized to support a fleet of large airplanes[(8)] flying a wartime rate of 10 hours per day would be 67 million tons for coal gasification to hydrogen, 61 million tons for coal gasification to methane, and 104 million tons for coal liquefaction to syncrude. Refer to Ref. 62 for NPC's postulated coal requirements.

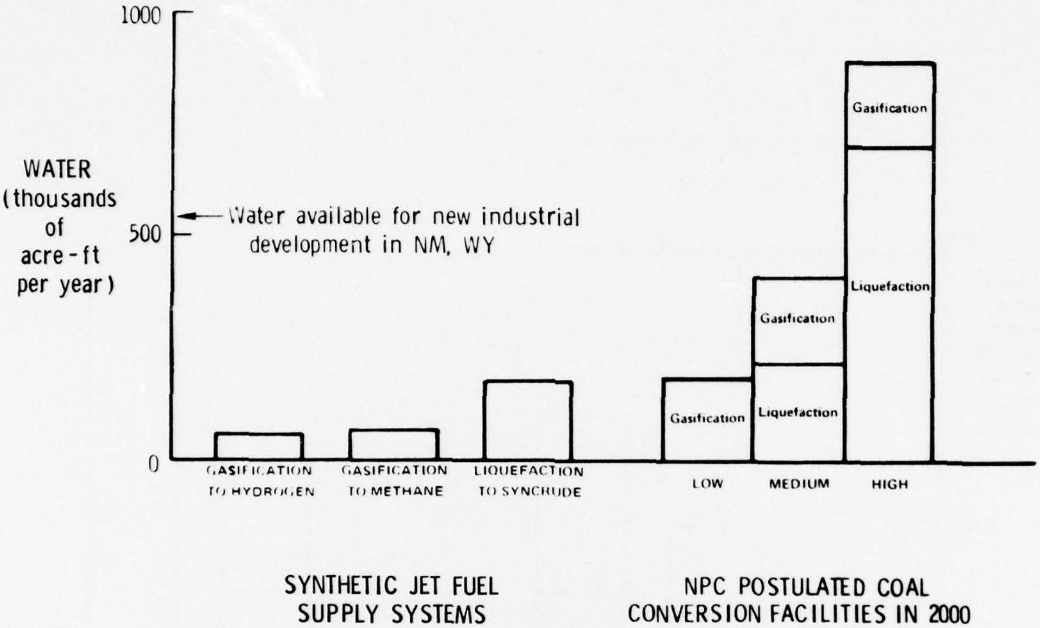
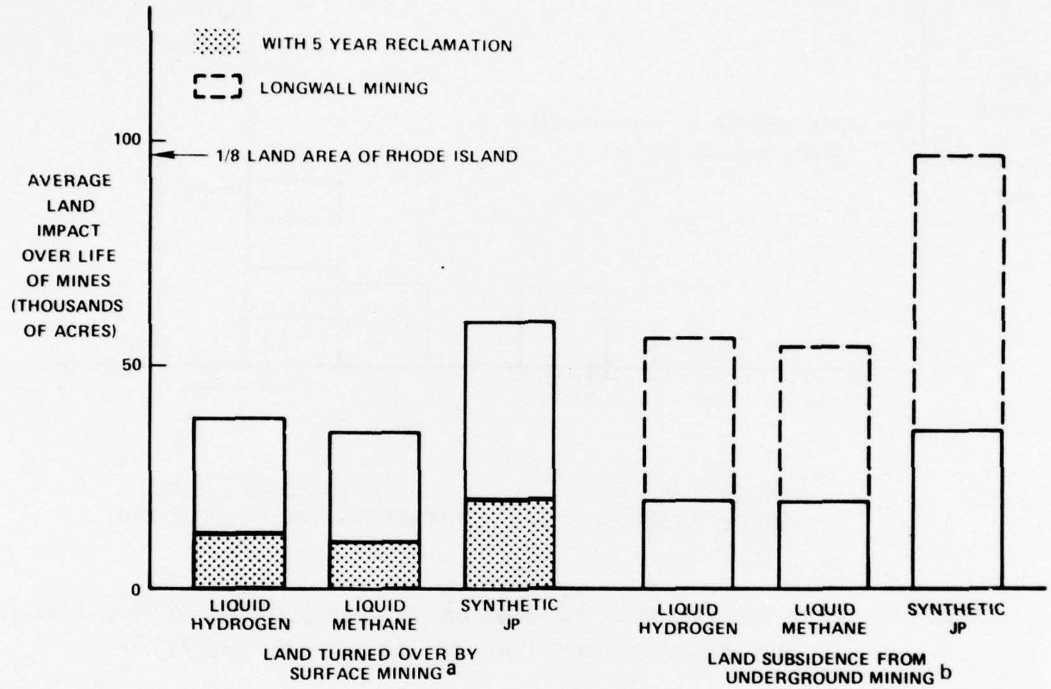


Fig. 32 — Water requirements for coal conversion facilities in New Mexico and Wyoming (from Refs. 31, 60, 62, 70, and 71)

in Fig. 32 indicate that additional costs may be incurred to develop new water supplies for the facilities, or additional distribution costs may be incurred to ship the coal to areas with more abundant water supplies.

Environmental Issues

The development of a synthetic fuels industry will create new sources of land, water, and air pollution. In the present analysis, a mix of eastern and western coal was used for the fuel supply systems to minimize distribution distances. Figure 33 shows the average land impact of the surface mining in Wyoming, New Mexico, and Alaska required to support the fuel supply systems of the three alternative jet fuels considered.[72] The land area that must be turned over in surface mining depends on the coal requirements of the fuel supply process, the coal recovery rate, the heating value of the coal, the coal density, and particularly, the thickness of the coal seam. For



[a]Annual surface coal production is analogous to that associated with Fig. 32 with the addition of assumed surface coal production in Alaska, which results in annual coal production of 83, 76, and 132 million tons for hydrogen, methane, and syncrude facilities, respectively.

[b]Annual underground coal production assumed to be 36, 35, and 61 million tons for hydrogen, methane, and syncrude facilities, respectively.

Fig. 33 — Impact on the land of coal extraction for synthetic fuels (from Ref. 72)

example, the average coal seam thickness in the Wyoming Powder River Basin is triple that of coal found in the Four Corners area of New Mexico (39 feet, as compared to 12 feet).[72] Hence, more land must be turned over in New Mexico than in Wyoming to obtain an equivalent amount of coal.

Figure 33 indicates a greater land impact for the synthetic JP alternative only because of the larger amount of energy being delivered. The land impact of the mining required to support the supply of liquid hydrogen reflects only the mining of coal needed to provide the resource energy for the process. If it is assumed that the process electricity for hydrogen liquefaction is also derived from coal, the land impact would be far greater than that shown in Fig. 33. The Rhode Island land area is used as a point of reference because some have suggested that in the United States an area somewhat greater than the land area of that state has already been stripped and not been reclaimed.

The ability to reclaim land overlying surface-mineable coal deposits is the subject of considerable controversy. If the mined land could be reclaimed in five years, the average land impact could be significantly reduced, as is shown in Fig. 33. Some suggest, however, that complete reclamation may be impossible. In that situation, in an absolute sense, the total amount of land turned over and unreclaimed would be twice that shown in Fig. 33.

The strip mining impacts shown in Fig. 33 are those that would occur in supplying part of the energy requirements for a fleet of very large airplanes.[8] If all of the Air Force's current jet fuel energy needs were to be supplied by western surface-mineable coal deposits, the amount of land turned over annually in the synthetic JP supply process could range from 1900 to 7000 acres, depending on whether Powder River Basin coal or Navajo coal from the Four Corners area were to be used. Hence, any major commitment by the Air Force to use jet fuels derived from surface-mineable western coal deposits could have a sizable land impact.

There is quite a different impact associated with underground mining--that of subsidence of the undermined area. The lower bars on Fig. 33 represent the land impact of room and pillar mining used to support the synthetic fuel supply systems for the East Coast air bases shown in Fig. 24. In room and pillar mining, the most prevalent type of underground coal mining practiced in the United States today, pillars of coal are left standing in the mine to reduce the amount of subsidence. Increased adoption of the longwall mining technique, in

which almost all the coal is removed, would enhance recovery but increase subsidence, as shown in Fig. 33.

In addition to the land impact of the coal mining required to support a synthetic fuels industry, the environmental pollutants from the coal conversion facilities must also be assessed. Table 7 compares the environmental pollutants from a conventional coal-fired steam power plant, a coal gasification plant, and a coal liquefaction facility, all sized to process an equivalent amount of coal.(72) These results must be interpreted with caution, since no commercial-size gasification or liquefaction facility has yet been built in this country. Indeed, one of the major objectives of the "information" program recommended by the Synfuels Interagency Task Force is to gain environmental impact data on synthetic fuel facility operations.(66) The estimates of coal conversion facility pollutants indicate that the new facilities may represent no greater threat to the environment than a conventional electric power plant, and perhaps less. In the case of air pollutants, the new facilities would remove most of the sulfur contained in the coal from a concentrated stream of hydrogen sulfide gas, rather than "scrubbing" sulfur dioxide out of the exhaust products of coal combustion. The "sludge" that results from this scrubbing process is one of the reasons the power plant has greater solid waste products. In addition, the coal conversion facilities recover some of the potential nitrogen air pollutants in the form of aqueous ammonia, rather than releasing them to the atmosphere as oxides of nitrogen. It is likely that much of this pollution control technology will be incorporated in future coal-fired power plants as well.

Finally, it should be noted that, while in comparison with a coal-fired power plant, the pollutant discharges from coal conversion facilities may not represent any increased threat to the environment, these plants may be built in areas of the west that now have a comparatively pristine environment, in which case they may represent a substantial threat to the environment in a relative sense.

Table 7

POLLUTANT DISCHARGE COMPARISON

Form of Pollutant	Pollutants Discharged (tons/day)[a]		
	1000 MWe Coal-Fired Steam Power Plant	Hi-Btu Coal Gasification Plant	Coal Liquefaction Plant
Water	4	0-10	0-14
Air	137	20-26	16-28
Solid	3230	826-1170	722-1110

SOURCE: Ref. 72.

[a]Assuming facilities operating at full capacity, with equivalent coal inputs.

UNCERTAINTIES IN THE EVALUATION

The assessment of fuel alternatives in this section has indicated that the production of synthetic JP requires less energy and is less costly than the other two alternatives. A related analysis of the use of the fuel alternatives in large subsonic military airplanes performing strategic airlift or station-keeping missions has indicated that for a broad class of missions, the synthetic JP alternatives would be more cost effective and energy effective than aircraft using the other fuel alternatives. Notwithstanding this fact, highlighted below are some of the uncertainties involved in the evaluation of the fuel production processes.

First, let us consider the initial coal conversion processes--coal gasification or liquefaction. It was postulated that all of the initial coal conversion processes used Lurgi technology, with the hydrogen process adding a water gas shift to enrich the gaseous product with hydrogen, the methane process adding a methanation step to enrich the gaseous product with methane, and the syncrude process using a high pressure H-Coal hydrogenation reactor to liquefy the coal using a hydrogen-rich gas produced in Lurgi gasifiers. The energy expenditures required for the Lurgi gasification process are relatively well understood, since it is a commercialized process, albeit not in the United States. However, considerable uncertainty does exist in the costs of Lurgi gasification.

The cost estimate for the high-Btu coal gasification plant being planned by the El Paso Natural Gas Company increased by a factor of five between 1973 and 1975 (then year dollars).[73] Since most of the coal gasification or liquefaction processes are sensitive to similar factors, such as costs of large pressure vessels, costs for equipment to handle and inject coal at high pressures, etc., each of the processes would probably experience similar escalations in costs for many items of equipment in the facilities. However, although it has been demonstrated quite successfully in small pilot plant operations, the H-Coal gasification reactor is still probably subject to greater uncertainties in energy requirements and costs than either water gas shift equipment or methanation equipment.

One interesting aspect in the relative comparisons between gaseous hydrogen and syncrude production processes is that about two-thirds of the plant investment for coal liquefaction by the H-Coal process is devoted to hydrogen production facilities.[46] Hence, it seems likely that any major technological advances that help reduce the costs or energy requirements for the production of hydrogen from coal will also directly benefit coal syncrude production, and possibly even syncrude refining, if supplemental gaseous hydrogen is required.

Of the second-stage energy conversion facilities, large-scale methane (or natural gas) liquefaction is probably the best understood. The refining of crude oil is also a mature, well-understood technology. One major uncertainty about coal syncrude refining centers on determining the optimum tradeoff between reducing the aromatic content of coal liquids at the refinery, or designing jet engines to use fuels of higher aromatic content. Hence, the basic technology elements to refine coal liquids exist on a commercial scale, with the definition of the mix of technologies to be used and the degree of processing desirable still to be specified.

Considerable experience has also been accumulated in liquefying gaseous hydrogen for the space program. However, production has been on a scale that is only a fraction of that required for aviation applications. Hence, while costs and energy expenditures for current small liquefaction facilities are relatively well understood, the

costs and energy requirements for larger facilities, and particularly the prospects for achieving the improvements in liquefaction efficiency already noted (including evolving improvements in electric power generation), are subject to considerable uncertainty.

Little uncertainty exists about the distribution system for synthetic JP. Today both crude-oil products and refined products are routinely distributed via pipelines; much the same is true of liquid methane, since natural gas (high in methane) is widely distributed in the United States; liquid natural gas is also routinely loaded and unloaded from tankers. Of course, modifications would be required for high volume throughput operations at airports.

In contrast to the other two alternatives, gaseous hydrogen is not routinely distributed long distances via high pressure pipelines. The literature suggests that no existing gaseous hydrogen pipelines have intermediate compressor stations,[21] hence, the economics and energy intensiveness of gaseous hydrogen pipelines are certainly subject to greater uncertainty than the other alternatives. Similarly, while a quarter-mile liquid hydrogen pipeline is used at the Kennedy Space Center for fueling space launch vehicles,[61] high volume distribution and fueling of aircraft with liquid hydrogen are subject to considerable uncertainty. The NASA Langley Research Center is currently attempting to resolve some of these questions about ground handling of liquid hydrogen at airports.[74-76]

Aside from uncertainties in the costs and energy requirements for energy conversion and distribution facilities, there seems little question that the domestic coal resource base is adequate to support production of any of the alternatives. However, the rate at which synthetic fuels will be introduced in the United States will depend not only on the development of the technology and the resource base, but also on a complex set of interrelated factors including national energy policies, world oil prices, the resolution of environmental and water availability issues, and the availability of investment capital. These considerable uncertainties exist and would tend to have an impact upon the development of any of three aviation fuel alternatives being evaluated.

RESEARCH AND DEVELOPMENT AREAS

The previous subsections have indicated that synthetic JP derived from coal would be less expensive to produce than the other alternatives both in an energy and in a cost sense and would have attractive characteristics for aviation applications. Synthetic JP also has the advantage of being far more similar to jet fuels in use today than the cryogenic alternatives, which should ease transitional problems for military users and promote its assimilation into a domestic fuels market now dominated by crude-oil-based fuels. What R&D areas, then, would have to be pursued if the Air Force is to prepare itself to exercise this fuel option in the future?

Table 8 highlights in very broad terms some of the key R&D activities that would be required to develop coal as a future source of jet fuels, with an indication of those agencies within the federal government that might sponsor the R&D either solely or in cooperation with the private sector. The three broad R&D areas address the central question: Do technology and economics dictate that major emphasis be placed on developing coal liquefaction and refining technologies to produce jet fuels that meet or approach current jet fuel specifications, or that jet engines be designed to operate efficiently on a wider range of possible fuels?

The items noted under liquefaction technology mainly refer to the progressive development from pilot-plant-size coal liquefaction facilities to demonstration-size facilities to define the economics, energy requirements, and environmental impacts of the candidate coal liquefaction technologies. This work clearly falls within ERDA's R&D charter and responsibilities. However, an inevitable part of this program would be an evaluation of the suitability of the various synthetic crude oils obtained from the different liquefaction technologies for alternative applications, including feedstocks for jet fuel production. Such a program would be required to ensure that the proper mix of technologies is developed to help meet the spectrum of civilian and military fuel needs in the future. Large quantities of coal synthetic crude oils will be required for refinery tests and subsequent full-scale engine tests for NASA and the DoD, including the Air Force, to

Table 8

R&D FOR THE SYNTHETIC JP OPTION

Technology	Potential Sponsors				
	ERDA	NASA	DoD	AF	Private Sector
Liquefaction Technology					
Establish sustained process feasibility	X				X
Identify most suitable refinery feedstocks	X	X	X	X	X
Determine feasibility and economics of large-scale operations	X				X
Refining Technology					
Improve catalyst technology		X	X	X	X
Determine optimum combination of catalysts and operating conditions		X	X	X	X
Establish jet fuel yield potential		X	X	X	X
Determine feasibility of large-scale refining of syncrude	X				X
Engine Technology					
Advance engine technology to allow relaxation of fuel specifications		X	X	X	X
Determine modifications for existing engines to use such synthetic fuels		X	X	X	X

determine the most suitable feedstocks for jet fuel production. Because ERDA has responsibility for developing and demonstrating coal liquefaction technologies, NASA and the DoD will be dependent upon ERDA to assure them of adequate supplies of coal syncrudes for R&D purposes.

The second broad technology area concerns defining the process requirements and economics of refining coal syncrudes into jet fuels. To do so will require identifying the most suitable catalysts and operating conditions for economically refining coal syncrudes. This work is currently being accomplished on a laboratory scale, the current activities already having been described. However, ultimately, the feasibility of coal syncrude refining will have to be demonstrated on a larger scale, perhaps under ERDA sponsorship in cooperation with the major oil companies.

The last category involves determining the financial, physical, and chemical effects of coal-derived jet fuels on military jet engines and fuel systems. If the commercial economics and technological difficulty are such that jet fuels refined from coal syncrudes will necessarily be higher in aromatic content than the jet fuels of today, then the engine designer must consider whether there are technological options available that would allow military engines to use fuels of higher aromatic content. For example, changes in combustor designs, fuel pumps, and fuel tank seals may be required to cope with fuels of higher aromatic content. To address these issues, the Air Force Aero-Propulsion Laboratory is currently using crude-oil-based jet fuels mixed with additives to imitate the characteristics of coal-derived jet fuels as well as using limited quantities of coal-derived jet fuels refined in laboratories. However, ultimately, large quantities of coal-derived jet fuels will be required for the full-scale tests that will determine the long-term effects of these fuels on military jet engines.

For several reasons, it does not seem at all clear that the Air Force can rely on NASA or on the other military services to accomplish the R&D necessary to develop the capability to use jet fuels derived from coal. First, the Air Force has been designated as the lead service for the development of improved aircraft turbines that may have to operate using synthetic jet fuels in the future. NASA emphasis on a synthetic jet fuel technology might focus on those economic issues to which the airlines are most sensitized. A fuel and engine technology developed for subsonic commercial applications might not meet high-performance military mission requirements. Finally, there is still some limited sentiment within NASA that the aviation fuel of the future is liquid hydrogen. From a military perspective, this does not appear to be a viable option. Hence, it would seem that the Air Force would have to assume at least part of the R&D burden if synthetic JP from coal is to be a viable jet fuel option for the military in the future.

The Air Force is entering an era when the economics and availability of jet fuel will be less certain than they have been in the

past. The Air Force may have to use jet fuels derived from a variety of primary energy resources, including crude oil, coal, and oil shale. The capability to use a variety of fuels may be one way in which the Air Force can maintain the operational flexibility that it has enjoyed in the past when fuel availability and economics were less of a problem.

The next section delineates the conditions under which it would be to the Air Force's advantage to acquire a multifuel propulsion capability and quantifies some of the possible benefits from having that capability. The R&D planner can then measure these benefits against his expectations of the costs of developing multifuel technology, some of those technology items having been highlighted in Table 8.

IV. POTENTIAL BENEFITS FROM DEVELOPING A MULTIFUEL PROPULSION CAPABILITY FOR FUTURE AIRCRAFT

INTRODUCTION

In the previous section, we indicated that coal and oil shale could be attractive domestic energy resource alternatives to crude oil for the future production of jet fuels. A synthetic JP fuel appears to be the most advantageous form derivable from these resources for use by the military. Synthetic JP fuels may have somewhat different characteristics than current petroleum jet fuels. The degree of difference will depend on the costs and technological difficulties of refining synthetic crude oils compared with the costs and technological difficulties of designing engines that could use broader specification jet fuels. Hence, R&D will be required to develop a multifuel propulsion capability (e.g., the capability of using fuels derived from crude oil, oil shale, or coal), with the ultimate balance between emphasis on refining or on engine technology yet to be determined. Ability to use a variety of fuels might significantly enhance the flexibility of the military because the Air Force would no longer have to depend on a single energy resource (e.g., crude oil) for future jet fuels. Of course, for the most part, such a capability would be valuable only if a synthetic fuels industry develops in the United States. The analysis presented in this section indicates a strong likelihood of this occurring sometime between 1990 and 2025, with the switch from crude-oil-based aviation fuels to coal- or oil-shale-based fuels in this time period being dictated by comparative economics rather than by a total lack of availability of crude oil.

At the present time, it is too early to tell how much it would cost to acquire the capability to use a variety of fuels. Nonetheless, the probable state of the geopolitical imbalance of crude-oil reserves at the turn of the century, in conjunction with the lead time required to develop and phase in new propulsion technologies, suggest that advanced basic research on the concept should start now. In the previous sections, we indicated that part of this R&D burden would probably have

to be assumed by the Air Force, a major domestic consumer of jet fuel, to assure a suitable fuel for use in military engines.

The analysis developed in this section indicates that in addition to the benefit of flexibility in wartime, there may be, under certain circumstances, a peacetime economic benefit associated with possession of a multifuel propulsion capability. Although the potential economic benefits from such a capability are extremely difficult to predict because of the future uncertainty associated with world and domestic prices for fossil resources, determination of potential benefits will, nonetheless, be the principal objective of this section. Specifically, we will seek to determine under what conditions an Air Force R&D investment in multifuel propulsion technology might result in an economic benefit.

Background

The life cycle through which a propulsion technology advancement evolves can last from 25 to 50 years. For example, it is not infrequent that a 5 to 10 year basic research effort precedes a 5 to 7 year engine development program, which then results in a 5 to 15 year production run of a family of engines, each of which has a 10 to 15 year life of operational usage, resulting in a total cycle of 25 to 47 years. Therefore, if a new propulsion technology is desired for aircraft operating around the year 2000, it is not unreasonable to expect that basic research should commence in the 1970s.

The Air Force Aero-Propulsion Laboratory has already initiated some limited research on the use of oil shale and coal as sources for future aviation fuels. Although NASA and the Air Force Aero-Propulsion Laboratory have undertaken a joint 10 year, $8 million study of synthetic aviation fuels derived from both oil shale and coal, they are placing a significant emphasis on oil shale. The emphasis on oil shale may in part be due to budget limitations. Although the research thus far has been promising, major questions still exist regarding the financial, physical, and chemical effects of synthetic fuels on jet engines and refinery operations. The problems posed by the characteristically high aromatic content of synthetic fuels (causing increased

combustor liner temperatures, greater smoke emissions, larger infrared signatures, etc.) and their high nitrogen content (causing catalyst poisoning in some refinery processes) need to be resolved. Furthermore, questions about ignition, thermal stability, material compatibility, etc., need to be explored. A significant amount of additional basic research will probably be needed; against the cost of that research, we can weigh the military value of the capability to use a variety of fuels and the potential economic benefit.

General Approach

The economic benefit that may ultimately be attributed to an R&D investment in the development of a multifuel propulsion capability will be influenced by three principal factors: (1) the resolution of a complex set of national energy policy issues; (2) the depletion of our domestic crude-oil reserves; and (3) the future price levels for crude-oil imports. Each of these factors is systematically considered in our assessment. For a given assumption about each of these factors, the economic benefit is assessed in terms of the cost avoidance opportunity that would be offered by the multifuel propulsion capability. If the Air Force were able to use a variety of fuels by 1995 (actually, some aircraft might be converted prior to 1995, others after 1995), then they could buy the cheapest jet fuel available that year rather than being forced to buy a perhaps more expensive crude-oil-based jet fuel.

For example, our analysis indicates that in the year 2000 the Air Force might spend $2 billion for jet fuel (1974 dollars) if they depended solely on jet fuels obtained from crude oil. On the other hand, if the Air Force could buy the cheapest fuel then available (whether derived from crude oil, coal, or oil shale), then they might spend only $1.6 billion annually on fuel. The cost avoidance attributable to the multifuel engine technology in the year 2000 would then be $0.4 billion (1974 dollars).

Data Sources. Principal data used in the analysis were extracted from the Stanford Research Institute (SRI) decision analysis that supported the President's Synfuels Interagency Task Force Report.[29]

The national energy policy scenarios formulated by ERDA were used as a representative set of possible national energy policies.[17] Data from the United States Geological Survey (USGS) were used to represent the alternative expectations of recoverable crude-oil resources in the United States.[77] And finally, although the Air Force annual consumption of jet fuel was assumed to remain constant at its current peacetime level of 3.9 billion gallons per year,* the results of the analysis are presented in such a way that they can be linearly scaled to other consumption levels.

It might be appropriate to consider reduced fuel consumption levels during peacetime, in light of the current trend towards decreasing fuel consumption as prices escalate and additional flight simulators become available. To the extent that such a trend continues in the future, the assumption that fuel consumption remains constant over time might cause the fuel cost avoidance potential to be overstated. Thus, if one believes that the Air Force's fuel consumption during peacetime might be reduced by 50 percent by the turn of the century, then one should correspondingly reduce the calculated cost avoidance by 50 percent.

The Model. Previous research has not been oriented toward forecasting jet fuel costs over the time scale of interest in this study. As a consequence, we employed a model developed at Rand[78] that uses an approach similar to that of the Brookhaven National Laboratory energy model, used in the development of ERDA's national energy policy scenarios.[79] The model used in our analysis, however, emphasizes the refinery sector and the temporal evolution of the U.S. energy system, whereas the Brookhaven model is a static model that does not consider the depletion of resources over time. The primary function of the model we used is to track the depletion of domestic resources by extraction cost categories ($6 per barrel of oil, $23 per barrel of oil, etc.), which enables a projection to be made of the cost of producing jet fuels from the primary fossil resources of interest.

It was our initial belief (subsequently indicated by our analysis) that a projected increase in extraction costs for domestic crude oil

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*Reference 5 and personal communication from William Vance, Defense Energy Information Service, October 1975.

from the current average of about \$6 per barrel to costs in excess of \$20 per barrel might provide an economic stimulus for the development of a synthetic fuels industry in the United States, which could ultimately lead to the near total replacement of crude oil as a liquid fossil fuel resource.

Because our model is relatively inexpensive to run, we were able to explore the sensitivity of future jet fuel production costs to a wide range of factors. This was accomplished by systematically combining a set of forecasts of future crude-oil import prices with alternative national energy policies and with a set of assessments of domestic crude-oil and natural gas reserves in order to simulate the range of alternative paths over which the United States energy system might evolve. For each simulation, the model was given a forecast of crude-oil import prices, a national energy policy scenario, an assessment of domestic fossil resources, and an assessment of the assumed demand for energy as a function of time, with the price elasticities of energy demands considered exogeneous to the model. The model, through a linear programming approach, then explicitly adjusts the rate of addition of energy conversion facilities (e.g., refineries, power plants) and the rate of resource depletion in order to minimize the cost of satisfying U.S. energy demands over the next 60 years. Hence, the decision to commercialize a given technology (e.g., production of synthetic fuels from oil shale) and interfuel substitution decisions (e.g., derivation of jet fuel from crude oil or from oil shale) are predicated on which technology minimizes the 60 year life cycle cost of satisfying U.S. energy demands. Because the model simulates the consumption of domestic resources over time, increases in resource extraction costs over time can be observed as consumption patterns force the U.S. energy system to resort to more expensive extraction methods (e.g., deeper wells).

The Economic Benefit Attributable to the R&D Program. For a given combination of national energy policy, crude-oil import price forecast, and assessment of domestic resources, the costs of producing jet fuels from crude oil, oil shale, and coal were estimated as a function of time. Then for each year commencing with 1995, the Air Force's

annual expenditure for jet fuel was estimated for two alternative cases. In case 1, the Air Force could procure only a jet fuel derived from crude oil, and in case 2, the Air Force could procure the least expensive jet fuel as derived from crude oil, coal, or oil shale. At worst, the annual expenditures for case 2 would be the same as for case 1 (e.g., if crude oil were the least expensive alternative). However, in those years when it would be cheaper to produce aviation fuel from coal or oil shale, there would be a net cost avoidance for case 2. This cost avoidance is the economic benefit that would be attributable to the R&D program (recall that there are other benefits, for example, enhanced military flexibility).

The economic benefit of the R&D program will be assessed in two steps. In the first step, the focus is principally on the cost of producing the alternative aviation fuels. Market price-setting mechanisms are then treated briefly in the second step, where the Air Force's market share is evaluated.

We begin the next subsection with a nominal projection of future jet fuel costs based on: (1) the ERDA synfuels scenario, (2) the nominal forecast for crude-oil import prices, and (3) the nominal assessment of the domestic fossil fuel resource base. These fuel cost projections are then used to assess the economic benefit attributable to a multifuel propulsion capability. The sensitivity of the economic benefit to other scenarios and resource cases (Fig. 34) is then addressed. The other scenarios include a baseline case with no major technology initiatives, a scenario in which improvements are made in the devices that use energy (e.g., autos, airplanes) a scenario in which breeder reactors constitute a major source of energy, plus various combinations emphasizing more than one technological approach. Since the foregoing aspects of the benefit assessment are by and large a cost analysis which does not purport to take into account marketplace supply and demand pricing, a limited attempt is then made to examine the sensitivity of the Air Force's crude-oil market share to the scenarios described above. Finally, the section is concluded with a summary of our observations.

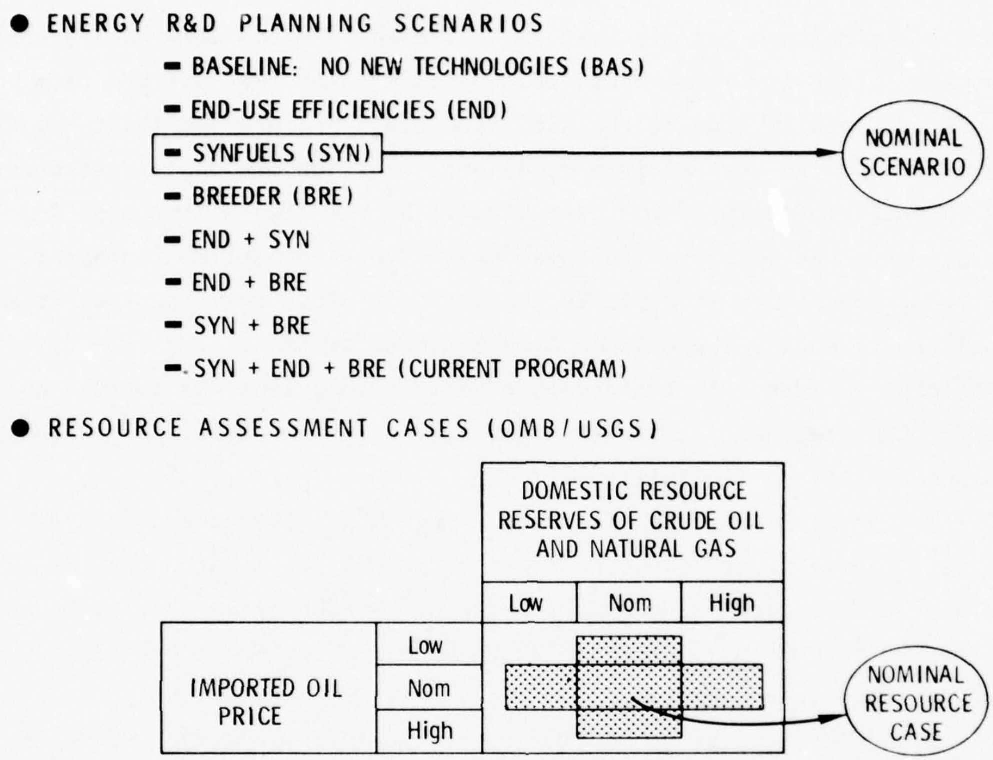

Fig. 34—Scenarios and resource cases (from Refs. 17, 29, and 77)

PROJECTION OF JET FUEL COSTS

We now make projections of the comparative cost of producing jet fuel from crude oil, coal, and oil shale, given: (1) a nominal assessment of the domestic availability of those resources, (2) the ERDA synfuels scenario as the national energy policy guideline, and (3) a nominal forecast for crude-oil import prices.

Data Sources

National Energy Policy. The ERDA synfuels scenario[17] is based upon the assumption that the United States aggressively pursues the research, development, demonstration, and commercialization of coal gasification liquefaction and oil-shale liquefaction in order to provide a lower-cost alternative to crude oil as a liquid fossil fuel resource. This scenario would have the effect of slowing down our rate of consumption of crude oil in the low extraction cost category,

thereby forestalling the need to resort to the extraction of higher cost crude-oil reserves.

Domestic Resource Base. The domestic resource assessment used in this section is a nominal estimate of the total resources that could be extracted at various costs (Fig. 35(a)). This assessment is based on the nominal estimates for demonstrated and inferred reserves reported in the President's Synfuels Interagency Task Force Report,[29] adjusted to include the expected undiscovered reserves estimated by the USGS.[77] The low and high estimates of domestic crude-oil reserves illustrated in Fig. 35(a) are considered in a subsequent sensitivity analysis.

The domestic resource extraction costs in Fig. 35(a) are for the resource delivered to the minemouth in the case of coal, the wellhead in the case of crude oil, and the wellhead in the case of *in situ* extraction of oil shale (or the output from the retort facility if it is mined). To facilitate comparisons, the resource supply costs are expressed in terms of the cost of a quantity of energy equivalent to that contained in a barrel of crude oil.*

Coal is the least expensive domestic resource on the basis of extraction costs per unit of energy as presented in Fig. 35(a). However, observe that raw coal is quite unsuitable for input to a refinery, whereas the shale oil is just one upgrading step away from being a comparable replacement for crude oil. When the cost of liquefying the coal is taken into account, the difference in cost between the shale oil and coal (shown by the curves in Fig. 35(a)) is altered substantially.

For our purposes, it is useful to present data on the cost of domestic resource extraction as a function of the cumulative consumption after a fixed point in time, as in Fig. 35(a). For example, the USGS estimated that the United States had somewhere between 50 and 150 billion barrels of oil that could be extracted at a cost of about $6 per barrel, as of the end of 1974.[77]

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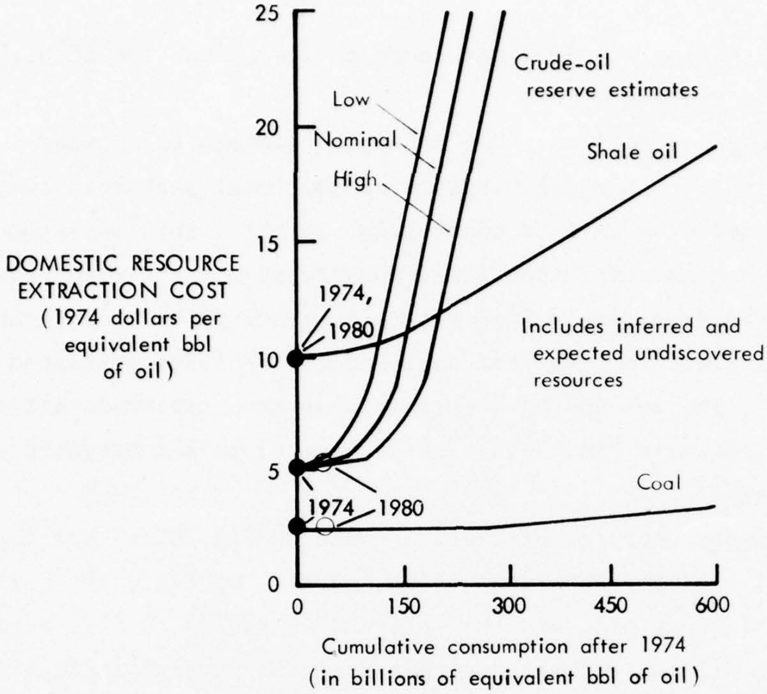
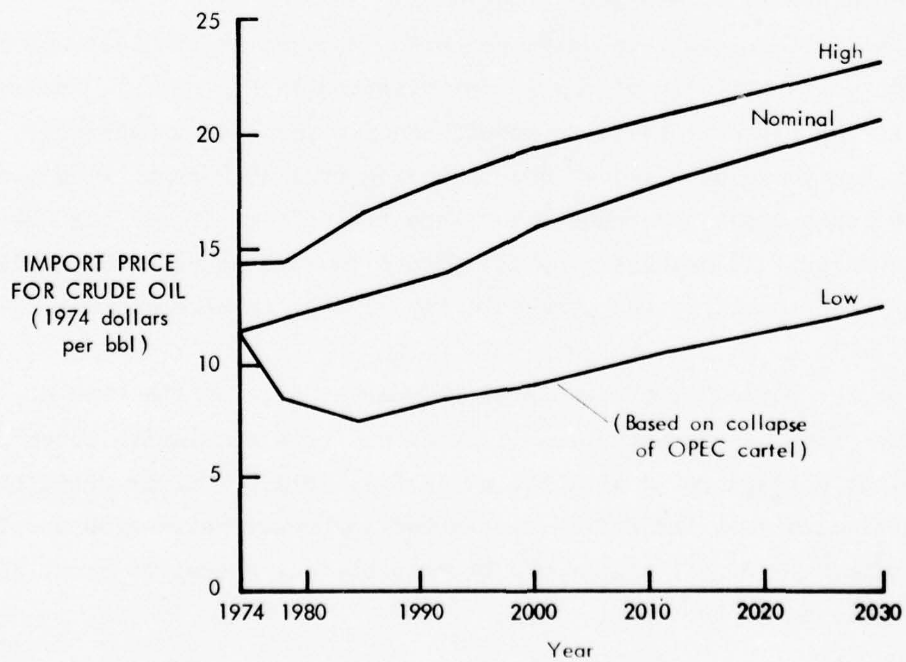
*A barrel of crude oil has an energy content of about 5.55 million Btu.



(a) Domestic resource extraction
(from Refs. 29 and 77)



(b) Import price for crude oil (from Ref. 29)

Fig. 35 — Resource assessment cases (model input)

Crude-Oil Imports. The data for crude-oil imports (Fig. 35(b)) could not be obtained on a basis comparable to that shown in Fig. 35(a) because of (1) the uncertainty about the extent of foreign reserves, (2) the extent to which nations other than the United States will deplete these reserves, and (3) the difficulty of predicting the future geopolitical conditions under which we might import crude oil. In view of these factors, we had to resort to using a range of subjective assessments of the future trend of the import price of crude oil as a function of time (see Fig. 35(b)). These assessments were formulated from the inputs of a number of government and industry experts who participated in the Synfuels Interagency Task Force study.(29) The nominal curve in Fig. 35(b), which is the basis for the jet fuel cost projections made in this section, reflects the assumption that the Organization of Petroleum Exporting Countries (OPEC) cartel remains an effective price-setting organization. The bottom, or low curve, on the other hand, reflects the price levels that might prevail if the price-setting effectiveness of the cartel were significantly weakened or collapsed. The upper curve shows the effect on the cost of oil if the price-setting effectiveness of the cartel were strengthened and could thereby extract an even higher price for crude oil.

The import price trends in Fig. 35(b) are extracted from the results of a decision analysis conducted by the SRI group which provided a principal input to the President's Synfuels Interagency Task Force Report.(34) The data in Fig. 35(b) in effect represent the spectrum of future events in terms of three scenarios: (1) an even stronger cartel; (2) survival of the current cartel's strength; and (3) a significantly weakened cartel. The experts who participated in the SRI decision analysis assessed the relative probability for these scenarios at: (1) a 0.25 probability for the first scenario (represented by the upper curve in Fig. 35(b)); (2) a 0.25 probability for the continuance of the current cartel's strength (represented by the nominal curve); and (3) a 0.5 probability for the weak cartel scenario (represented by the low curve).(34)

Projections of Resource Consumption

Given the nominal assessments of resource supply cost as a function of year in the case of imports, and as a function of cumulative consumption in the case of domestic resources, the next step is to determine the consumption patterns over time for the domestic fossil resources of interest. This was done with a model that simulates the evolution of the U.S. energy system and the consumption of our domestic fossil resources.[78] The resulting resource consumption pattern is depicted in Fig. 36, in terms of the cumulative consumption of resources after 1974 for coal, shale oil, and crude oil. (Again, the units are in terms of the equivalent energy content of a barrel of oil).

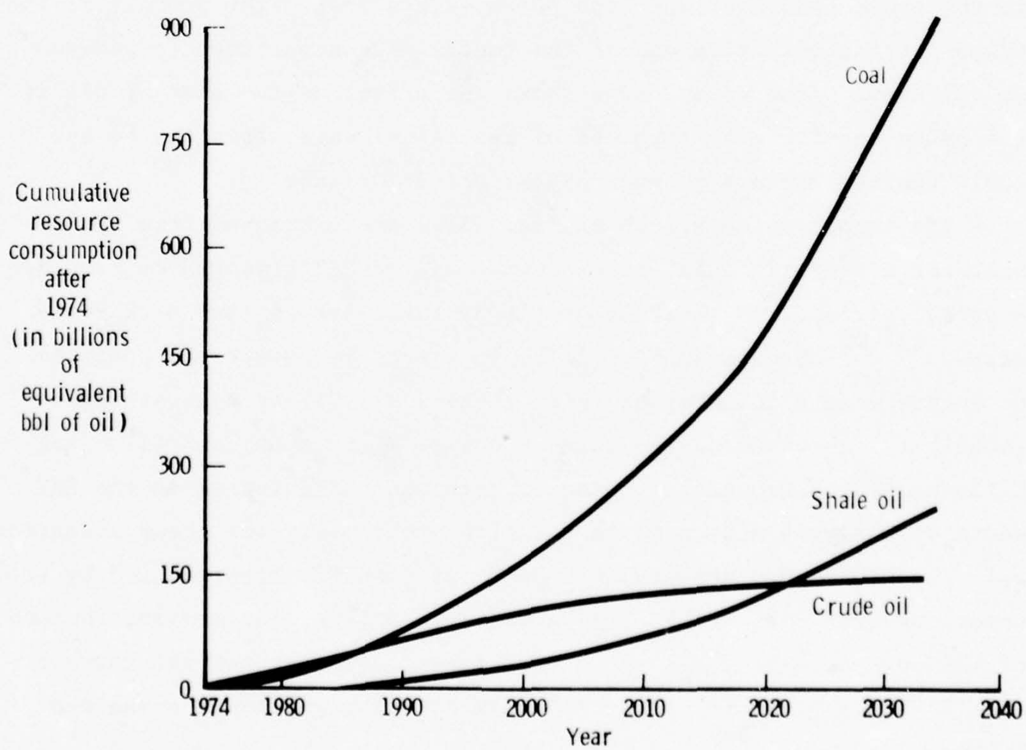


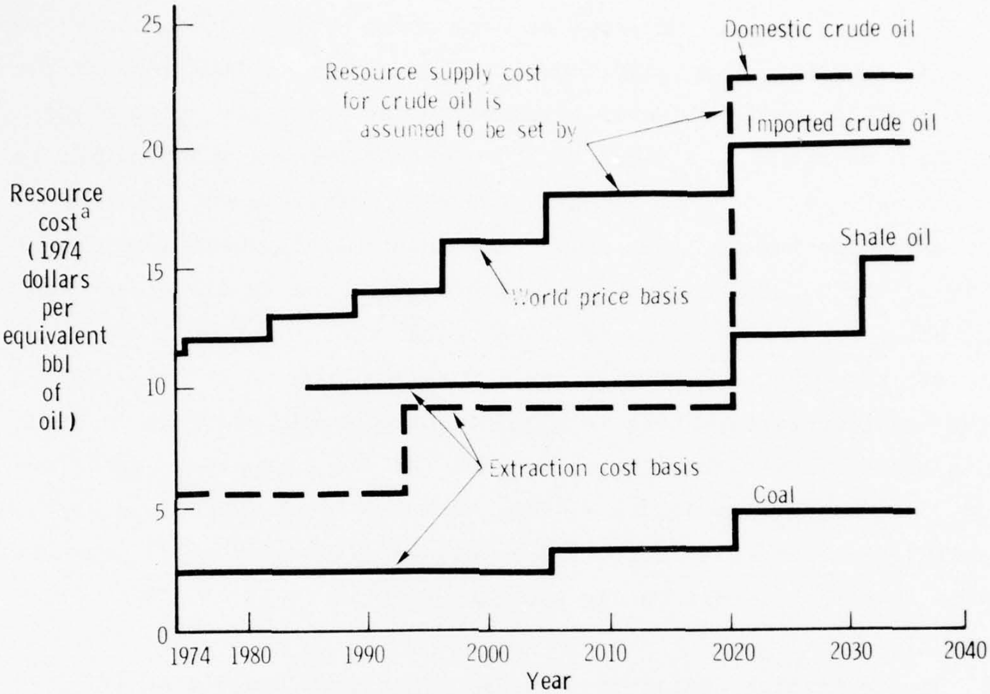
Fig. 36—Projection of cumulative consumption of domestic fossil resources

In a given year, the slope of each curve in Fig. 36 indicates the corresponding annual consumption rate. For example, the slope of the curve showing cumulative coal consumption becomes quite steep after 1990 in contrast to the slope of the crude-oil curve, which begins to flatten out. By 2020, the annual production of crude oil has become virtually nonexistent. The reason for this shift from consumption of crude oil to consumption of coal and oil shale can be discerned from Fig. 35(a) by observing the relative shapes of the curves showing domestic resource extraction costs. Once the knee in the crude-oil curve is encountered, there is significant economic pressure to replace crude oil with coal or oil shale. As the extraction costs for crude oil continue to increase, that resource becomes less and less desirable as a primary energy resource, and eventually all energy users switch to other primary energy sources, such as coal, oil shale, or uranium.

From a military point of view, it might seem beneficial if everyone else switched to coal or shale oil, simply leaving the remaining crude-oil reserves for the military to use. However, our results indicate that by the time other users shift to coal and shale oil, the crude oil in the lower extraction cost category would have been depleted, leaving only more costly crude oil for military use (see Fig. 37).

Projection of Jet Fuel Production Costs

Resource Costs for Jet Fuel Production. The primary energy resource cost projections in Fig. 37 are based on the cumulative consumption trends of Fig. 36 and the resource supply costs of Fig. 35. The imported crude-oil price curve is taken directly from Fig. 35(b). The other three curves (for domestic crude oil, shale oil, and coal) are developed from the simulation by simply combining the information in Figs. 35(a) and 36. The steps in Fig. 37 for the latter three curves represent increases in the extraction cost for the corresponding domestic resources. For example, by the early 1990s, all of the domestic oil that could be extracted for $6 per barrel will have been depleted, thus causing a shift to the extraction of oil at the $9 per barrel level. Similarly, there is another shift to the $22 per barrel



[a]Costs for domestic crude oil at the wellhead, coal at the minemouth, shale oil at the wellhead for *in situ* extraction or output from the retort facility for surface operations, imported crude oil at U.S. ports.

Fig. 37 — Resource costs for jet fuel production (data on imported crude oil from Ref. 29)

category in the year 2020. It is this latter shift that drives the remaining crude-oil users to an alternative primary energy resource, such as coal or oil shale.

Of course, actual shifts in extraction costs are more evolutionary than the discrete shifts depicted in Fig. 37. However, the figure does illustrate the two fundamental facts: (1) as resource consumption continues, extraction costs increase (especially for crude oil, since it is in much shorter supply); and (2) higher costs for crude oil drive energy users to other primary energy resources. Again, the data in Fig. 37 are presented in terms of costs per unit of equivalent energy in a barrel of oil.

Impact of Resource Costs on Production Costs. Figure 38 depicts the relationship between jet fuel production costs and the resource supply costs for the three primary energy resources of interest.[79,80] On each of the three curves, there is a benchmark (the solid circle)

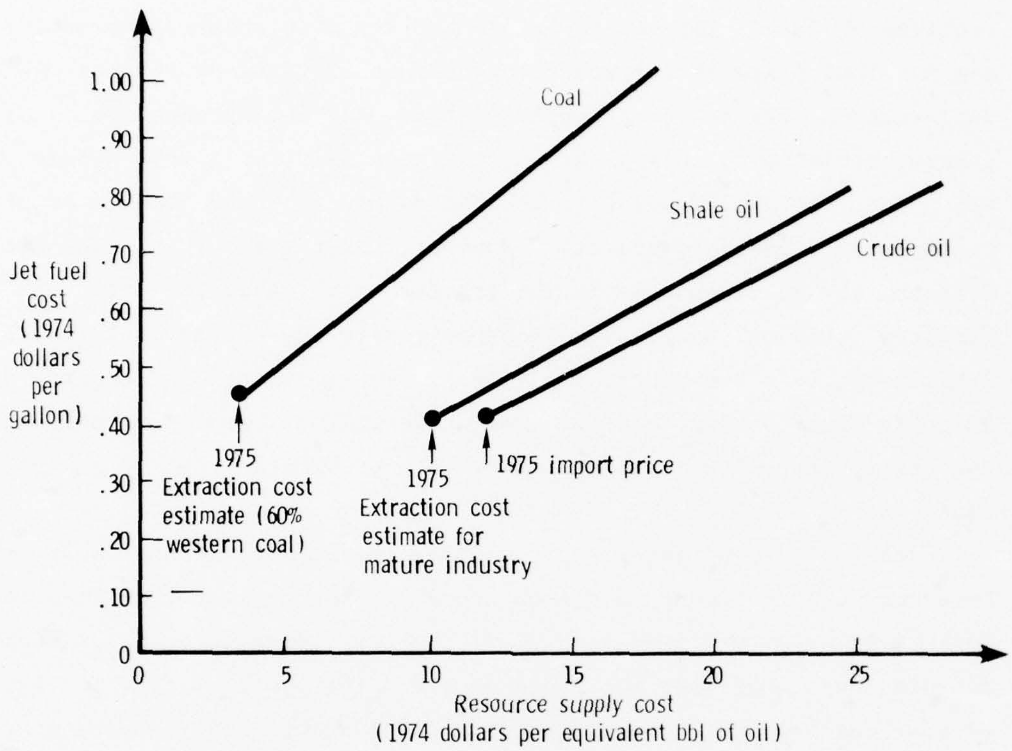


Fig. 38—Jet fuel production costs (from Refs. 79 and 80)

that indicates what the current production cost would be if the indicated primary energy resource were being used today to produce jet fuel. Since jet fuel is produced exclusively from crude oil today, the benchmarks for the coal and shale oil curves are hypothetical. Nonetheless, they indicate that at current resource supply cost levels, jet fuel could be produced for roughly the same cost from any one of the three alternatives (i.e., coal, shale oil, or crude oil). Thus, the relevant question is: *How rapidly will the resource supply cost escalate over time for the three primary energy resources?* That question was answered directly in Fig. 37 for coal and oil shale.

However, in the crude-oil case, the issue is complicated by the appearance of two resource supply cost curves in Fig. 37. In Fig. 38, we assumed that the crude-oil resource supply cost is based upon the import price for crude oil in 1975. As long as the United States

requires crude-oil imports to supplement domestic crude-oil production, the marginal price of imported crude oil should set, or exert a strong influence on, the resource supply cost for jet fuel production.* Of course, strictly speaking, this is the case only for a free market, which does not wholly exist in the United States today because of price controls on domestic crude oil. However, under the current decontrol program, the government is in the process of allowing the price of domestic crude oil to rise to an uncontrolled level that will, in all likelihood, be close to the import price level. Thus, in determining the cost of producing jet fuel from crude oil, it seems reasonable to use the import price as the basis for the crude-oil resource supply cost.

Jet Fuel Production Costs. Although it is more expensive to produce jet fuel from coal than from crude oil for a given resource supply cost† (Fig. 38), we found in Fig. 37 that the resource cost for coal is much lower than that for crude oil, and therefore we find in Fig. 38 that for certain combinations of coal and crude-oil resource supply costs, jet fuel produced from coal could be less costly than a similar jet fuel produced from crude oil. Note that our results indicate that there are intervals of time (Fig. 39) during which jet fuel produced from oil shale might be less costly than that produced from coal and vice versa. Considering the level of uncertainty of the analysis, the relevant observation about Fig. 39 is not, however, that small differences in production costs may exist between jet fuels from coal and shale oil, but rather that potentially significant differences in costs may exist between jet fuels derived from crude oil and the other two competing resources.

It should be kept in perspective that as oil shale liquefaction technology (i.e., *in situ* or retort) develops and as environmental

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*As of July 1975, the Air Force was paying 42 cents per gallon for JP-4, which is essentially commensurate with jet fuel production costs at a resource supply cost equivalent to the world oil price.

†For example, if both coal and crude oil had a resource supply cost of $15 per equivalent barrel of crude oil, jet fuel produced from coal would be about twice as costly as jet fuel produced from crude oil.

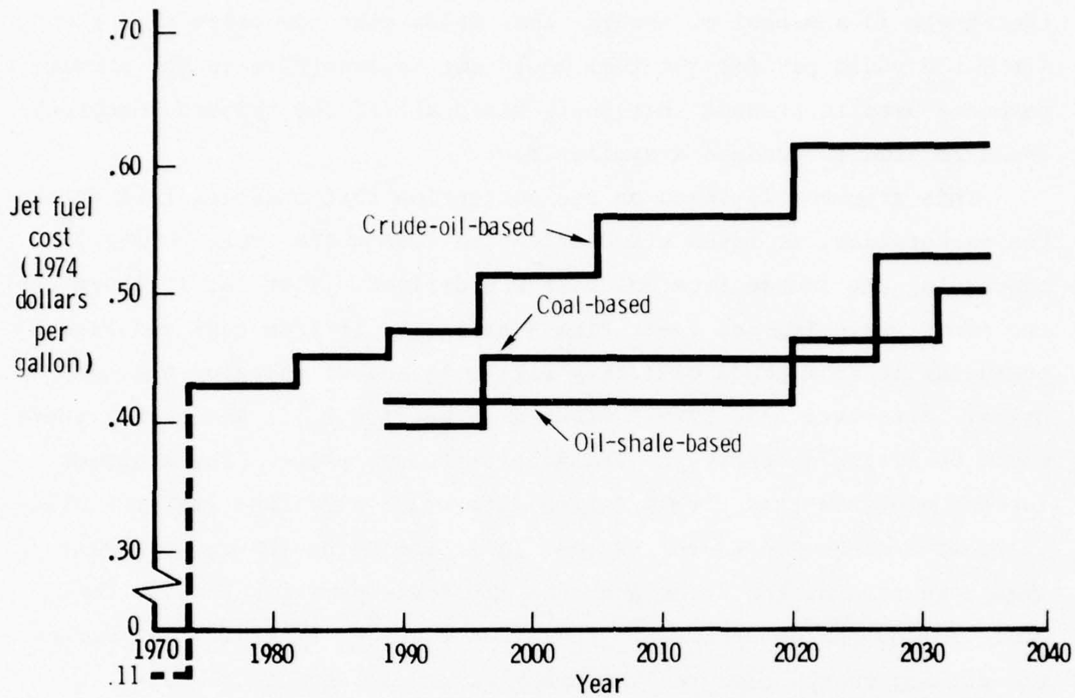

Fig. 39—Projection of jet fuel production costs (model output)

issues and reclamation costs become more certain, it is quite possible that the oil-shale alternative may lose some of its advantage over coal or even crude oil. Similarly, there are technology and cost uncertainties associated with full-scale commercialization of coal liquefaction, which could also alter the cost projection for coal-derived jet fuels. Since these uncertainties will not be resolved for some time, it seems that the development of a multifuel propulsion capability would have the distinct advantage of freeing the Air Force from reliance on just a single energy resource and associated jet fuel production technology.

An Alternative View of Market Behavior. Thus far, the focus has been principally on the cost of producing aviation fuel from alternative primary energy resources. With the exception of the imported oil price-setting the resource supply cost for crude oil, we have thus far purposely steered clear of any attempt to consider the marketplace price-setting mechanisms that might be in effect at the turn of the century. For the sake of completeness, however, we must acknowledge

that there is a school of thought that holds that the price that the Air Force would pay for jet fuel would not be sensitive to the primary resource used to produce that fuel, since all of the primary resources could be used to produce a similar fuel.

This argument is based on the contention that once the fuel enters the marketplace, it loses all distinction (not quite true, however)* concerning the source from which it was derived. That is, if there are two firms producing jet fuel, Firm A producing it from coal and Firm B producing it from crude oil, they will both end up charging the same price. Alternatively, Firm A might also be Firm B, in which case there would be little incentive to charge a different price. The argument further contends that Firm A (which uses crude oil) must charge a price that, at a minimum, covers its cost (cost including return on investment); therefore, the price that the Air Force pays for its jet fuel would follow the crude-oil projection in Fig. 39, regardless of whether the primary energy resource was crude oil, coal, or oil shale.

One fault in this argument lies in the assumption that Firm B (using coal) would be allowed to charge the same price as Firm A (using crude oil).† First of all, this would allow an excess profit situation to exist for Firm B, and secondly, such a situation would be counter to the stated objective of national energy policy, which is to develop secure sources of energy for the future that provide lower-cost alternatives to crude oil.[81] It does not seem credible that the public would support government investment in energy technology research, development, and demonstration (and perhaps even commercialization) and would then allow prices to be set for energy products in a manner which is in direct opposition to the objectives of the R&D investment. Thus, in the remainder of this report, we will assume that coal and oil-shale resources and the eventual end-use product of interest (i.e.,

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*For example, the aromatic content of jet fuels may differ, depending on the energy resource from which they are derived, and the extensiveness of the refining process.

†Another fault with the argument is that it assumes that there is no competition between firms of type B that use coal to produce jet fuels.

jet fuel) are priced on a cost basis (including appropriate return on investment) rather than on the basis of the prevailing crude-oil price.

THE ECONOMIC BENEFIT REALIZED BY THE AIR FORCE

We now use the jet fuel production cost projections just developed to assess the potential benefit attributable to a multifuel propulsion capability that might result from an Air Force R&D program.

If, optimistically, the Air Force were to possess such a capability fleetwide in the early 1990s, then it could commence procurement of the lowest-cost jet fuel alternative at that time. Figure 39 indicates that based on presently available information, coal- or oil-shale-based jet fuels could be consistently less costly by then than jet fuels derived from crude oil. Hence, there could be a significant economic advantage in not having to procure crude-oil-based jet fuels.

Figure 39 also suggests that there may be time periods during which coal-based jet fuels are cheaper than oil-shale-based jet fuels, and vice versa, depending on the rate at which lower-cost surface-mineable western coal deposits are depleted, as well as on the rate at which the most readily recoverable oil-shale deposits are depleted. Thus, it would seem highly desirable not to rely on a single resource for jet fuel, but rather to develop a capability to use jet fuels derived from coal, oil shale, or crude oil. In so doing, the Air Force could procure the lowest-cost alternative at any point in time to exploit the switching phenomenon suggested by Fig. 39.

The R&D Benefit

For the case where the Air Force possesses a multifuel propulsion capability, it is assumed that the least-cost jet fuel alternative depicted in Fig. 39 is used each year. For the case in which the Air Force does not have this capability, it is assumed that the annual consumption is of a crude-oil-based jet fuel, which is procured at the cost indicated in Fig. 39. The resulting projection of annual jet fuel expenditures by the Air Force (Fig. 40) is based on the assumption that future Air Force fuel consumption remains constant at the current peacetime level of about 3.9 billion gallons per year.

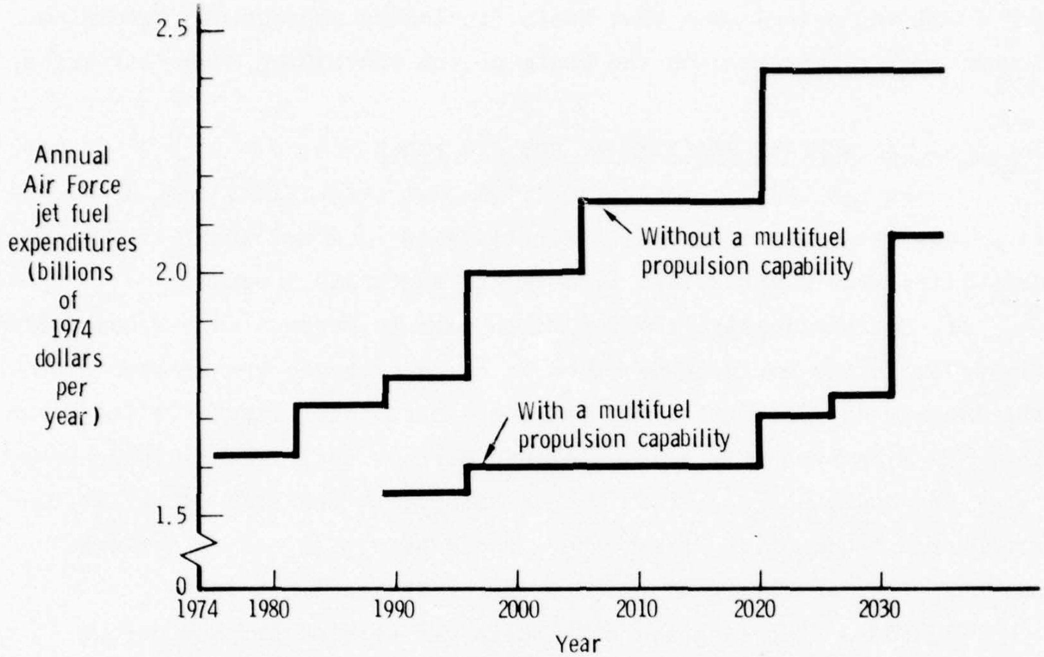

Fig. 40—Projection of annual jet fuel expenditures by the Air Force

The curves in Fig. 40 represent the annual expenditures for these two cases. The difference between the two curves represents the potential cost avoidance that can be attributed to the multifuel capability. When the Air Force could actually begin procuring synthetic jet fuel would depend on the outcome of R&D efforts and the subsequent implementation of the technical knowledge derived from the R&D effort. In one circumstance, the pacing item might be the rate at which refineries could be built or adapted to refine synthetic crude oils into jet fuels with specifications similar to those in use today, in which case only modest refinements to Air Force jet engines might be required. In another circumstance, if the results of the R&D program dictated that synthetic jet fuels would of economic necessity have characteristics different from those in use today, then the major pacing item might be the time required to develop and install new engines in the Air Force fleet.

For the latter case, even if engines procured as early as 1985

possessed a multifuel capability, it would probably be 2005 before most of the fleet could be converted (giving an average conversion date of 1995). Since an in-depth analysis of the conversion problem is not included in the present analysis, we will simply assume, for present purposes, that the average conversion date is 1995. We recognize, of course, that actual conversion dates would depend upon the technical difficulty, as well as economic considerations.

According to the assumption of an average fleet conversion in 1995, the Air Force would commence accrual of cost avoidances attributable to the multifuel propulsion capability in 1995, as illustrated on the top of Fig. 41 (the top curve in Fig. 41 is simply the difference between the two curves in Fig. 40). We observe that, around the turn of the century, the approximate savings would be about $400 million per year. On a cumulative basis, that would amount to nearly $12 billion (1974 dollars) over the period 1995 to 2020 (note that this is almost one-half of the Air Force's current annual budget). The discounted present value of that stream of cost avoidances is illustrated in the bottom third of Fig. 41. Even with a 10 percent discount rate applied to uninflated dollars, the 1980 present value of the savings stream from 1995 to 2020 amounts to $1 billion.*

The $1 billion (1974 dollars) 1980 present value benefit provides a tentative answer to the question of what it might be worth (from an economic standpoint) for the Air Force to possess a multifuel propulsion capability by the turn of the century. Thus, if it was felt that such a capability could be obtained for a total cost having a 1980

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*Over the years, it has been the accepted standard practice in the Office of Management and Budget (OMB) to use a 10 percent annual discount rate on an uninflated dollar stream when making comparisons between program alternatives (e.g., no multifuel program versus a multifuel program). Of course, the real interest paid on long-term treasury notes is closer to 5 percent. Thus, part of the 10 percent discount frequently used by OMB contains a margin against uncertainty. That is to say there is some possibility that the program will not achieve its original goals. (Simply as a point of arithmetic interest, the 1980 present value with a 5 percent discount rate would amount to $3 billion (1974 dollars).) The discounted present value is stated relative to 1980, because that is the year in which we expect that major R&D expenditures to develop a multifuel propulsion capability might be initiated.

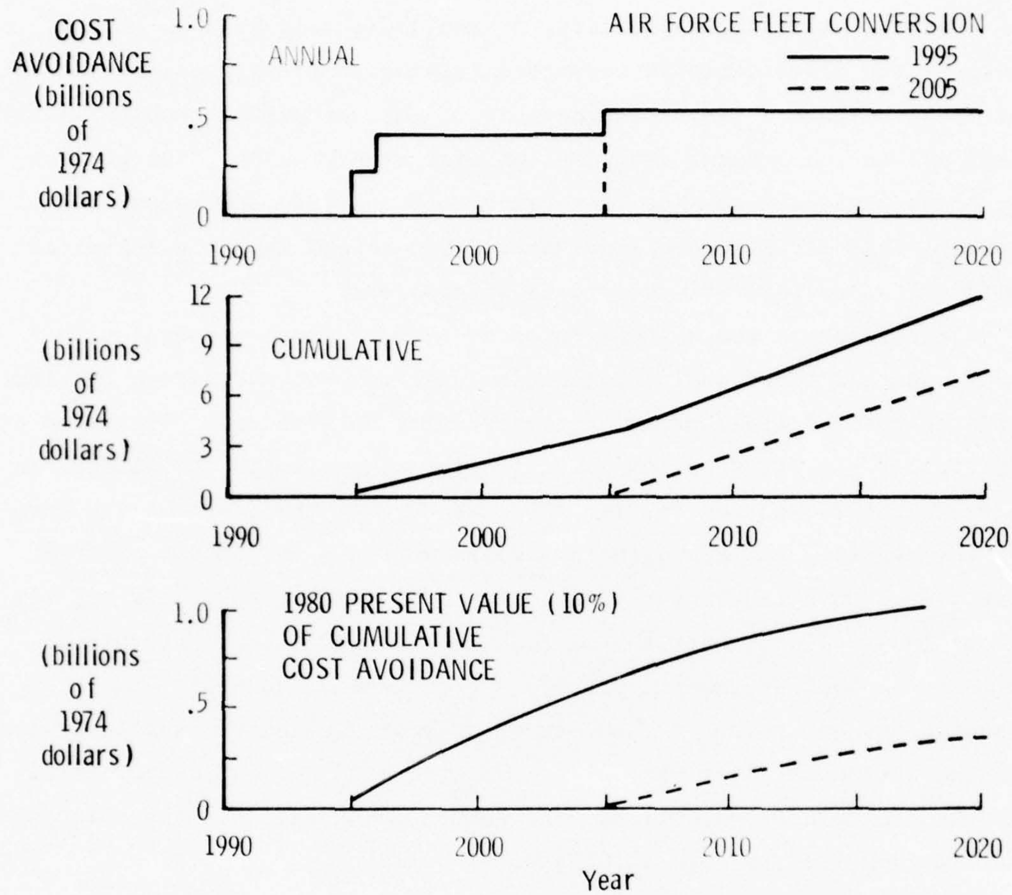

Fig. 41 — Cost avoidance attributable to a multifuel capability

present value of less than \$1 billion in 1974 dollars, then the program could be justified on economic grounds (questions of enhanced military flexibility not considered).

The outstanding question at the present time is whether the 1980 present value of the expenditures required to achieve a multifuel propulsion capability would be less than the \$1 billion benefit. While presently available information is not adequate to make an overall assessment of the Air Force expenditures that would be necessary to achieve a multifuel capability, we can note that one component of multifuel R&D would likely be an engine technology demonstrator program to determine possible engineering changes that would be required to burn synthetic jet fuels in military engines. This type of R&D rarely costs more than \$50 million--a fairly modest expenditure when compared

with the possible benefits.[82] Recognize that if new engines are required, the cost of acquiring the capability would include not only the R&D cost, but also any incremental acquisition, procurement, and operations costs. However, as long as the incremental acquisition and procurement costs are reasonably small, they may not have much effect because they would be incurred during the 1990s and thus at a 10 percent discount rate would be considerably discounted. A reasonable first-order assumption might be that the R&D costs would dominate the present value of the cost of acquiring the multifuel propulsion capability.

Cost of Deferring the R&D Program

One question that frequently arises in the evaluation of an R&D program is whether the program can be deferred a few years, or whether the initial level of effort can be reduced. The dashed curves in Fig. 41 can be used to develop some insight about the value of time for this particular R&D program. For example, if we make the assumption that a ten-year delay in the R&D program corresponds to a ten-year delay in the implementation of the multifuel capability, then the benefit stream shown at the bottom of Fig. 41 simply shifts downward an amount equal to the benefit that would be forgone during the first ten years (i.e., \$0.6 billion).

In effect, we have assumed that a ten-year delay in the R&D program would cause the average fleet conversion date to slip by ten years, from 1995 to 2005. This ten-year slip would cost \$0.6 billion in cost avoidances that would not be accrued. Thus the "cost" (in 1980 present value terms) of a ten-year shift in the program could amount to \$600 million (1974 dollars), or \$60 million per year.

This analysis (and the associated assumptions) suggest that the Air Force should be willing to spend up to \$1 billion (1974 dollars, 1980 present value, 10 percent discount rate) to acquire a multifuel propulsion capability and that the cost of slipping the acquisition of such a capability by ten years could amount to \$0.6 billion (1974 dollars, 1980 present value, 10 percent discount rate). One interpretation of these results is that it would not be unreasonable to invest several tens of millions of dollars per year in the early 1980s

to acquire this capability. Such an investment in the early 1980s probably warrants an investment in the late 1970s of several million dollars per year in preparation for the 1980s program. One of the early objectives of this research should be to assess what the total cost of developing and procuring a multifuel capability would be. Such an assessment should be accomplished by the end of the 1970s prior to an escalation of the investment rate in the early 1980s.

The results and discussion presented thus far have been based on the ERDA synthetic fuels scenario and the nominal assessment of the domestic energy resource base, and the nominal assessment of the import price for crude oil. We will now examine the sensitivity of the 1980 present value benefit to alternative national energy policies, alternative assessments of domestic crude-oil reserves, and alternative assessments of the future import price for crude oil (e.g., see Fig. 35).

SENSITIVITY TO OTHER SCENARIOS

Since it is impossible to accurately predict the future course of national energy policy, the discovery of domestic crude-oil resources, and the trend in the import price for crude oil, it is essential that the results of the previous section be examined in the context of a wide range of alternative scenarios. To do this, we utilized a model[78] that would dynamically simulate the evolution of the entire U.S. energy system. Because of the efficient character of that model, we have been successful in exploring a wide range of alternative national energy policies, including virtually all of the new technology elements of the three ERDA energy R&D planning scenarios[17] and the five resource cases indicated in Fig. 34.

We will discuss only those scenarios that turned out to be most relevant with respect to their impact on the results of the previous section. These scenarios can be described in terms of the ERDA synfuels scenario and two parameters: the imported oil price and the assessment of the crude-oil and natural gas resources case. The two sets of assessments for these parameters yield the nine resource cases depicted in Fig. 42.

[PROBABILITY OF OCCURRENCE]

		ASSESSMENT OF DOMESTIC CRUDE OIL AND NATURAL GAS RESERVES		
		LOW [.1]	NOMINAL [.8]	HIGH [.1]
IMPORTED OIL PRICE	LOW [.5]	0 [.05]	0 [.4]	0 [.05]
	NOMINAL [.25]	1.0 [.025]	1.0 [.2]	1.0 [.025]
	HIGH [.25]	1.9 [.025]	1.9 [.2]	1.9 [.025]

EXPECTED COST AVOIDANCE = $.7 BILLION

NOTE: 1980 present value in billions of 1974 dollars; 10% discount rate, Air Force fleet conversion in 1995.

Fig. 42 —Sensitivity of cost avoidance to alternative scenarios (probabilities taken from Ref. 29)

The nominal result already obtained for the 1980 present value benefit is for nominal imported oil price and for a nominal assessment of domestic crude-oil reserves. With the high imported oil price assessment, the benefit is nearly doubled, whereas with the low imported oil price assessment, there is no benefit when expressed in 1980 present value terms. Thus, if the OPEC cartel collapses and the low imported price scenario is realized, it will be more economical to continue to procure a jet fuel from crude oil than from oil shale or coal well into the next century.

The current assessment of the experts who participated in the SRI decision analysis is that there is a 0.5 probability of the low imported oil price scenario occurring.[29] Given that probability, there then is a 50 percent chance that the Air Force would accrue no economic benefit from a multifuel engine technology capability (which would

obviously cost something to develop and procure). On the other hand, there is a 0.25 probability that the high imported oil price scenario will occur, in which case the 1980 present value benefit of the multifuel engine technology capability would be nearly \$1.9 billion. By multiplying the expected benefit in each cell in Fig. 42 by the probability (appearing in brackets), we find that the expected cost avoidance, on a probabilistic basis, would be \$0.7 billion in 1980 present value (1974 dollars).

It is curious to note that the benefit appears to be insensitive to the assessment of domestic crude-oil and natural gas reserves. This is because the crude-oil resource cost (Fig. 37) is driven by the world price of oil until the year 2020. The reason for including an assessment of domestic crude-oil reserves as a sensitivity parameter will become apparent when we take up the subject of marketplace pressures.

From this sensitivity assessment, we conclude that there is a definite possibility that the Air Force might accrue no benefit between 1995 and 2020 from a multifuel propulsion capability and, in fact, could suffer a loss (that being the cost of the R&D and any incremental procurement and operating costs). However, we also conclude that, based on a probabilistic treatment of a wide range of alternative scenarios, the expected 1980 present value benefit (\$0.7 billion) is quite close to the result of the nominal case.

MARKETPLACE "PRICE PRESSURES"

A potentially significant limitation of the analysis thus far stems from our deliberate avoidance of marketplace price mechanisms, except when treating the resource cost for crude oil, where it was assumed that the domestic crude-oil price would be set by the import price. One way of making a preliminary assessment of the potential marketplace "price pressure" is to consider the market share that peacetime Air Force jet fuel consumption would represent if the Air Force continued to procure only a crude-oil-derived jet fuel.

For example, recall that Fig. 36 showed that the annual consumption of crude oil was virtually eliminated by about 2020, as evidenced by the flat slope of the cumulative consumption curve for domestic

crude oil. If the Air Force were to persist in using only crude oil as a jet fuel source, then it might be virtually the last crude-oil consumer in the market. Such an independent posture could potentially leave the Air Force vulnerable to price-gouging by suppliers. Furthermore, since Air Force peacetime jet fuel needs are only one-half to one-quarter those that might be required during a wartime situation, the Air Force could pay a significant economic penalty during peacetime for the underutilization of the crude-oil refiner's capacity.

The marketplace posture of the Air Force could begin to deteriorate as soon as significant synthetic fuel production capacity began being developed. For example, if the other jet fuel consuming members of the aviation sector were among the first users of crude-oil-based products to switch to synthetic fuels, the Air Force might then be the only jet fuel consumer that did not have the flexibility to use a jet fuel derived from synthetic fuels. Of course, there is no way of knowing today whether the aviation sector will be one of the first to switch.

However, it is relevant to note that the commercial airlines might be able to switch more rapidly than the Air Force because of the shorter average engine life (calendar life) due to higher annual utilization levels. Thus, it is conceivable that as soon as there is a significant synthetic fuel production capability, the Air Force may begin to experience marketplace "price pressures" which could drive up the price that the Air Force pays for jet fuel beyond the production cost projections in Fig. 39.*

To assess the interval of time over which the Air Force can expect the onset of marketplace "price pressures," we will consider two extreme cases: (1) the U.S. commercial aviation sector is the first to

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*We recognize that there is an alternative view of market behavior that runs counter to this argument; however, the consequences are no less foreboding to the Air Force. The alternative view is that if commercial aviation were also to persist in using jet fuels from crude oil, the increased competition for the diminishing resource could result in a bidding contest for available jet fuel supplies, in which case a greater economic penalty might be involved than if the Air Force were the only user of jet fuels derived from crude oil. In either case, an Air Force policy of relying solely on jet fuels from crude oil could place it in an awkward negotiating posture.

switch to synthetic jet fuels, and (2) the U.S. commercial aviation sector is the last to switch to synthetic jet fuels (see the bottom of Fig. 43). This switching process can be viewed in terms of the percentage of the annual jet fuel production that still comes from crude oil. For example, Fig. 43 shows that in the scenario where the aviation fuel sector aggressively pursues a switch to synthetic fuels, the switch could commence as early as 1935 and be completed by the year 2000. Of course, there is some question about whether the engine technology could be made available as early as 1985.

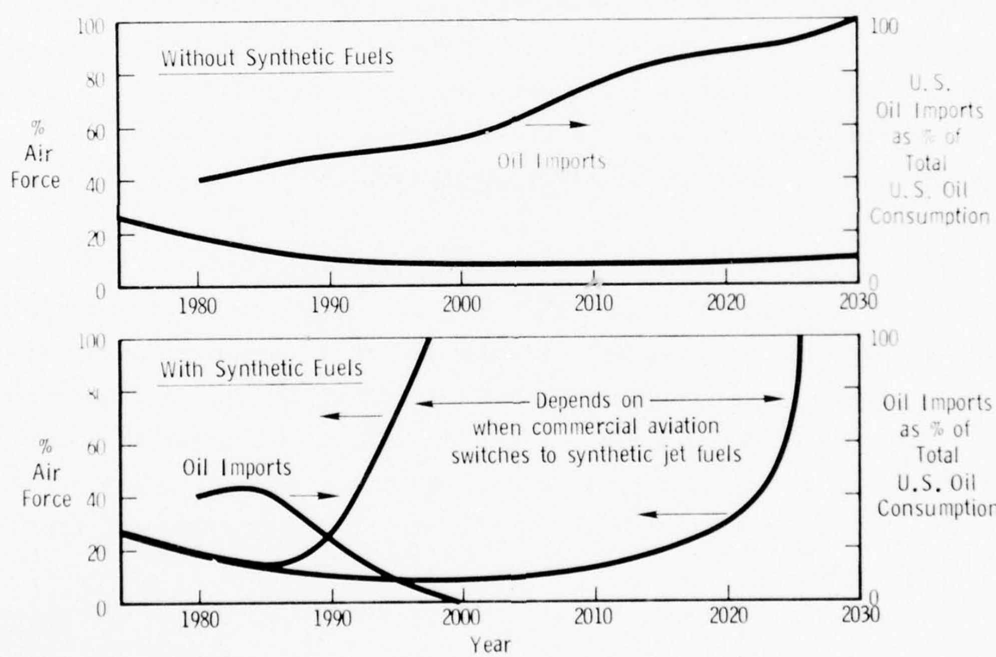

Fig. 43—Air Force share of U.S. consumption of jet fuel produced from crude oil during peacetime

If the aviation sector commences a switch to synthetic fuels in 1985, then the Air Force could begin to experience market price pressures as early as 1990, based upon an assumed wartime consumption rate of four times the current peacetime consumption rate (Fig. 44). This can be seen in Fig. 44 by observing when the Air Force's wartime

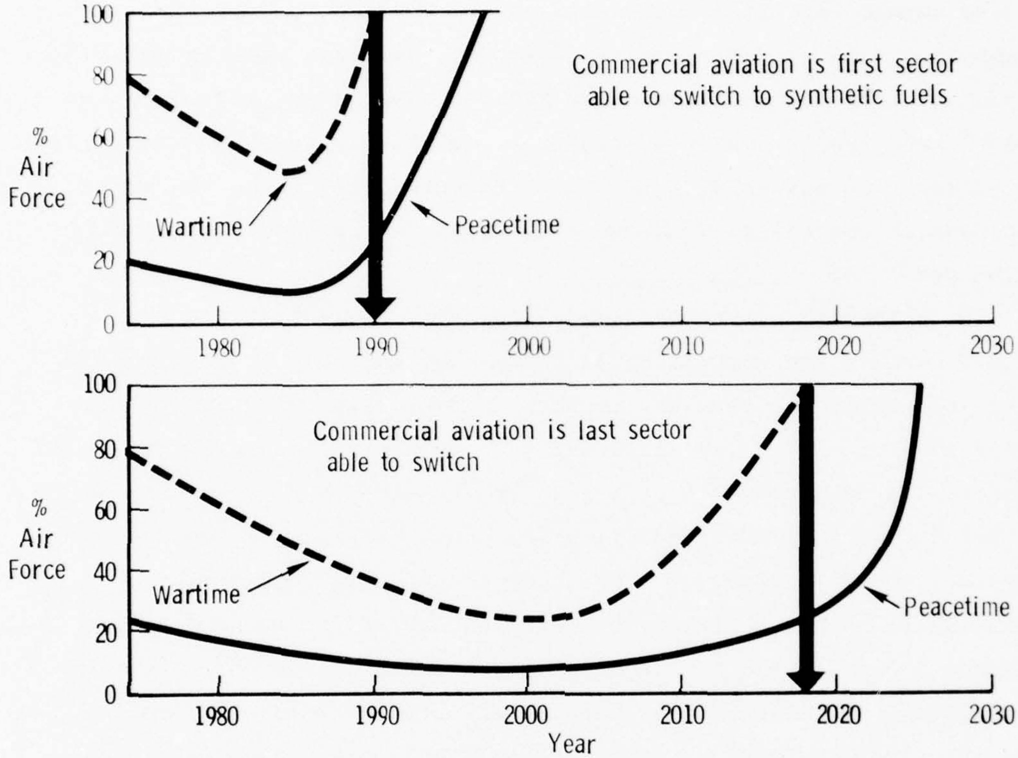

Fig. 44—Air Force share of U.S. consumption of jet fuel produced from crude oil

requirement curve goes to 100 percent of the production of crude-oil-derived jet fuel. The Air Force jet fuel consumption curve declines with time on a percentage basis because we have assumed that the Air Force consumption remains constant while the commercial sector's consumption continues to grow at a 4 percent rate (per the ERDA synfuels scenario).(17) The ERDA assessment of commercial aviation fuel consumption may be on the high side in light of recent airline experience and the projected introduction of fuel-conservative aircraft in the 1990 time period. However, these considerations do not change the central thrust of the present analysis, and therefore, for the sake of consistency, we have retained the ERDA assumptions.

If the aviation sector is the last to switch to synthetic fuels, we observe that the Air Force must switch by the year 2018 simply

because beyond that time there will not be sufficient capacity on line to supply the assumed wartime requirement. However, waiting until 2018 is probably not advisable on other grounds because the Air Force can consume from two to four times as much fuel during wartime than in peacetime. The analysis of Sec. III indicated that there can be a cost penalty associated with underutilizing fuel production capacity during peacetime.

The principal point to be made from Fig. 44 is that the Air Force's marketplace posture could become increasingly more vulnerable due to the switching of other sectors to synthetic fuels during the period 1990 to 2018. The sensitivity of this result to other relevant scenarios is summarized in Fig. 45. The results in Figs. 43 and 44 are for the nominal imported oil price and the nominal assessment of domestic crude-oil reserves. The most threatening combination of scenarios is found in the lower left-hand corner of the matrix in Fig. 45. It appears that if the low assessment of domestic crude-oil reserves is realized, and if the high imported oil price scenario is realized, then the Air Force could expect marketplace "price pressures" to develop in the 1990 to 2008 time period. Fortunately, however, current expert opinion is that there is only a 0.05 probability of this outcome. Yet, the probability that marketplace price pressures will commence in the period 1990 to 2018 has been estimated to be 0.45. Thus, there does appear to be almost a 50 percent chance that the Air Force will be in, at best, an awkward marketplace negotiating posture at the turn of the century if it does not possess a multifuel propulsion capability.

OBSERVATIONS

Eventually, there will be a switch from crude-oil-based jet fuels to coal- or oil-shale-based fuels. This will probably occur sometime between 1990 and 2025. The switch will be motivated by comparative economics rather than by the total lack of availability of crude-oil reserves. There will still be significant crude-oil reserves available at the time the switch takes place; however, the cost of extracting these reserves will be such that crude oil will no longer be a viable

[PROBABILITY OF OCCURRENCE]

		ASSESSMENT OF DOMESTIC CRUDE OIL AND NATURAL GAS RESERVES		
		LOW [.1]	NOMINAL [.8]	HIGH [.1]
IMPORTED OIL PRICE	LOW [.5]	2024 [.05]	2026 [.4]	2026-2034 [.05]
	NOMINAL [.25]	1990-2008 [.025]	1990-2018 [.2]	1990-2026 [.025]
	HIGH [.25]	1990-2008 [.025]	1990-2018 [.2]	1990-2026 [.025]

Fig. 45—Air Force "period of critical interest"

alternative to the long-term availability of both coal and oil shale, with their relatively low extraction costs.

It will probably be easier for the commercial aviation sector to switch to a multifuel or synfuel engine technology due to: (1) shorter equipment lives, (2) steady consumption levels, (3) less stringent fuel specifications, and (4) fixed route structures. Due to the high cost and low peacetime utilization levels for military aviation equipment, it is not at all uncommon for equipment to be in the inventory for 20 to 25 years. Commercial airlines, however, generally plan on a 12 to 15 year equipment life. As an example, compare the current fleet of KC-135 tanker aircraft that still operate on turbojet engines and the commercial airline's 707. (The 707 is of the same family as the KC-135.) Virtually all of the old turbojet-powered 707s have been either retired or retrofitted with more efficient turbofans. However, the high cost of such an engine retrofit has prevented the Air Force

from affording such a luxury for the KC-135 fleet. Many of the KC-135s that were procured in the 1960s will probably be inventory aircraft well into the late 1980s.

The nonsteady-state nature of Air Force fuel consumption requirements is a special problem that is not experienced by the commercial aviation sector. The surge in Air Force wartime fuel consumption could amount to more than 300 percent of the peacetime consumption level in a high-intensity conflict. The Air Force also must require a much more stringent set of specifications for the fuels used by its combat aircraft. For example, while the commercial airlines might not be unduly concerned about a moderate increase in the aromatic content of their jet fuels, it could be a significant concern to the Air Force because it might significantly increase the visual and infrared signatures of engine exhausts, thereby reducing the survivability of the Air Force aircraft in a combat environment. Finally, the airlines enjoy a fixed route structure, whereas the Air Force must be able to respond worldwide. All of these issues tend to suggest that the problem of switching fuels might be much more significant for the Air Force than for the commercial airlines and therefore would probably include other than simple economic considerations.

A NASA-developed engine technology for subsonic commercial aircraft might well focus exclusively on economic issues to which the airlines are most sensitive. This, however, might be entirely inappropriate for the Air Force. In particular, observe that there is still some sentiment within NASA that the most economic solution for the commercial airlines is to adopt liquid hydrogen as the jet fuel of the future. The results of Sec. III indicate that liquid hydrogen is an unacceptable fuel alternative for the Air Force (except, perhaps, for specialized missions).

The present value benefit of a multifuel propulsion capability for the Air Force is probably worth about $1 billion (1974 dollars) in 1980 present value terms. The cost of deferring the implementation of such a technology for five years would probably cost the Air Force about one-third of a billion dollars (1974 dollars) in 1980 present value terms. Notwithstanding the arguments of some individuals, that

liquid hydrogen is the most economical future jet fuel for the commercial airlines, we tend toward the opinion that some form of a multi-fuel propulsion capability would also well suit the needs of the airlines. If the airlines were to adopt such an engine technology in lieu of relying solely on crude oil as the energy source for future jet fuels, the 1980 present value benefit to the commercial aviation industry could be from $4 to $10 billion, depending upon market growth and the outcome of the NASA fuel-conservative aircraft program. Furthermore, the sheer magnitude of commercial aviation's jet fuel consumption (perhaps 4 to 10 times that of the Air Force at the turn of the century) indicates that any delay in their transition to a multifuel capability could result in an economic loss greater than any the Air Force might experience from postponing the transition, despite the fact that they might be able to effect the transition in a shorter time period.

Since the commercial aviation sector stands to lose much more than the Air Force in terms of the aggregate economic impact, it is quite reasonable to ask why the Air Force should develop a multifuel propulsion capability when obviously the commercial aviation sector has much more at stake. Would it not be more reasonable for NASA to develop such a technology? However, as we indicated previously, it is not clear at this point that a NASA-sponsored solution for the commercial aviation sector would be at all suitable for the more stringent requirements that the Air Force is likely to have. If the Air Force were to acquire a significant lead in R&D in this general area, some advantage might be realized in subsequent negotiations with NASA over future cooperative R&D efforts.

V. CONCLUSIONS

United States supplies of economically recoverable crude oil are rapidly being depleted. While the United States still has a significant resource base of crude oil, those resources will be extractable in the future only at costs considerably greater than those prevalent today. As the largest DoD consumer of jet fuel derived exclusively from crude oil, the Air Force faces a major problem today and in the future.

This report has focused on some of the technological options that might tend to reduce Air Force jet fuel consumption in the short term and perhaps ultimately lessen or eliminate total Air Force reliance on crude-oil-based jet fuels in the future. Our findings indicate that the Air Force propensity for keeping aircraft in the fleet over very long life cycles (15 to 20 years or more) works to their disadvantage when it comes to adopting cost-effective measures for saving jet fuel in the short term and exacerbates planning for the long term when jet fuels may be derived from domestic energy resource alternatives to crude oil.

In the short term, retrofitting high-fuel-consuming Air Force aircraft with new turbofan engines appears to be a highly energy-efficient measure; however, because of the high procurement costs for new engines, the low level of peacetime flying, and the advanced age of the aircraft at the conclusion of the retrofit program (average ages on the order of 15 years or more), savings in jet fuel expenditures would not be adequate to offset the costs of the modification, even with fuel prices significantly higher than those prevailing today.*

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*This conclusion is based on a comparison of engine retrofit costs and the fuel cost savings experienced by an entire fleet of retrofitted aircraft. We have not considered the case in which enhanced capability offered by the new engines is used to allow retirement of a portion of the fleet, which could also offer cost reductions. Or conversely, one could attach a monetary value to possible enhancements in capability (e.g., greater range) of an entire fleet undergoing an engine retrofit.

For much the same reason, most of the proposed aerodynamic modifications, while saving energy do not appear to offer the potential of full cost recovery through savings in jet fuel expenditures. One possible exception to this conclusion is an aerodynamic modification to the C-141A, in which it might be possible for costs to be fully recovered, depending on the ultimate cost of the modification and the service life of the aircraft. In general, costs may be fully recoverable through savings in jet fuel expenditures if modest aerodynamic modifications are accomplished early in the life cycle of the aircraft. Unfortunately, most of the major fuel-consuming aircraft in the Air Force fleet are well along in their life cycle.

What then are the long-term prospects for reducing the Air Force's reliance on crude-oil-based fuels, given that short-term technological modifications do not appear particularly attractive? National energy policies, and in particular the R&D policies of ERDA, will have a major impact on the availability of synthetic fuels for Air Force use in the future. Our research results indicate that there is a strong likelihood that a major coal and oil-shale synthetic fuels industry will develop in the United States between 1990 and 2025, and that the switch from crude-oil-based aviation fuels to coal- or oil-based fuels in this time period will be dictated by comparative economics rather than by a total lack of availability of crude oil. Our analysis further indicates that the most desirable jet fuel form derivable from coal or oil shale is a synthetic JP, similar to but not necessarily identical to crude-oil-based jet fuels in use today.

If the Air Force is to exploit the availability of synthetic jet fuels in the future, significant R&D remains to be accomplished to fully understand the implications of synthetic jet fuels on refinery operations and military jet engines of the future. Because NASA-directed R&D on synthetic fuels will probably focus on those economic issues about which the airlines are most concerned, it seems likely that at least part of the synthetic fuels R&D burden will have to be assumed by the Air Force, a major consumer of jet fuels, to assure a suitable fuel product for military use.

Since the life cycle through which a propulsion technology

advancement evolves can represent a 25 to 50 year time period, it would seem prudent that the Air Force assign a high priority to this research now. This research should have as a goal the determination of the proper technical and economic balance between synthetic crude-oil refining requirements and possible changes to engines to accommodate synthetic jet fuels such that fuels derived from crude oil, oil shale, and coal can be utilized in military jet engines of the future. One of the immediate objectives of such a research program should be to resolve as much of the uncertainty as possible about the ultimate costs of developing and implementing a multifuel propulsion capability. Possession of the capability would allow procurement of the least costly fuel alternative in the aviation fuel marketplace and would lessen the Air Force's present total reliance on a single resource (e.g., crude oil) for its jet fuel needs.

The 1980 present value economic benefit between 1995 and 2020 of possessing such a capability resulting from the R&D program could amount to about $1 billion (1974 dollars). If the foreign oil cartel were to break, leaving no immediate economic stimulus for the development of a domestic synthetic fuels industry, any economic benefit to the Air Force between 1995 and 2020 would be postponed such that the 1980 present value benefit would be negligible. However, in this circumstance, crude-oil imports could be supplying 90 percent of U.S. crude-oil needs by 2020--an undesirable situation with many attendant national security and economic problems. With the continuance of a strong cartel, and the development of a synthetic fuels industry in the United States, an Air Force policy of relying solely on crude oil for its jet fuel needs could place it in, at best, an awkward marketplace negotiating posture by the turn of the century. Furthermore, by the time other energy users begin shifting to coal and shale oil, crude oil in the low extraction cost category will have been depleted.

Appendix
U.S. ENERGY RESOURCE BASE

The material contained in this appendix provides supplementary and background information to the overview of U.S. domestic energy resources presented in Sec. III, following the same categorization scheme as that illustrated in Fig. 21. The material on coal resources developed in this appendix was used to identify and select major representative surface- and underground-mineable coal deposits as the resource supply points for the analysis of a coal-based jet fuel supply system.

CARBONACEOUS NONRENEWABLE RESOURCES

Domestic U.S. carbonaceous nonrenewable energy resources, or fossil resources, consist primarily of crude oil, natural gas, coal, and oil shale, with significantly lesser quantities of bituminous tar sands. By virtually any estimate, the energy embodied in U.S. coal resources dwarfs that of any other fossil energy source (Fig. 46). Despite this fact, coal supplies less than 20 percent of U.S. energy needs, primarily because petroleum products and natural gas burn cleaner, are far easier to handle than coal, and have been more economical.

Coal Resource Base

The USGS groups coal resources into identified resource and hypothetical resource categories. Identified resources are those which have been determined on the basis of mapping and exploration. The hypothetical resources are determined by extrapolation of the data on identified resources into unmapped and unexplored areas. The identified resources are subdivided into measured, indicated, and inferred categories, primarily on the basis of the spacing of the points of observation, roughly 0.5, 1 to 1.5, and greater than 2 miles, respectively. Resources are further subdivided by depth of overburden and the coal seam thickness.[83,84]

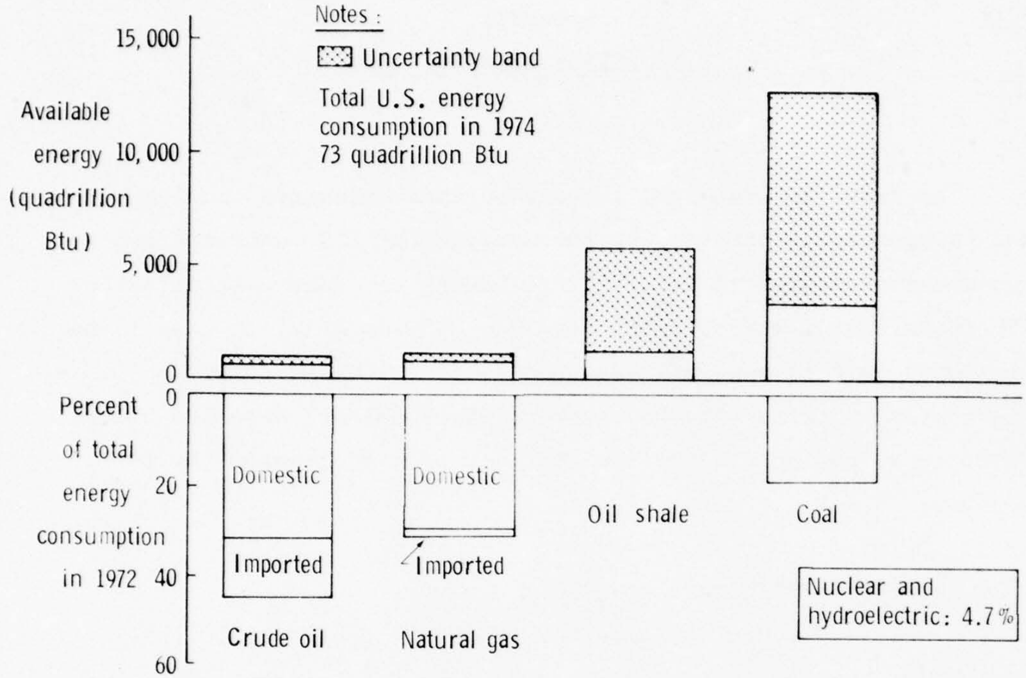

Fig. 46—Recoverable U.S. fossil resources (from Refs. 17 and 62)

Using this categorization scheme, the USGS estimates that there are about 1581 billion tons of identified coal resources remaining in the ground and about 1643 billion tons in the hypothetical category. The categorization of the identified resources according to seam thickness and reliability of the resource estimates is noted in Table 9. Measured against current U.S. coal production of about 0.6 billion tons per year, these identified resources are vast. However, far less than 100 percent of the in-place coal resources are amenable to mining given today's extraction technology and economics. For example, coal in thin beds and coal in beds more than 1000 feet below the surface are of little current economic interest. The USGS considers coal within 1000 feet of the surface in seams of intermediate thickness as a paramarginal resource which will be of increasing economic interest and importance in the future.(84)

The U.S. Bureau of Mines, Department of Interior, in developing one of the most recent estimates of the demonstrated U.S. coal reserve

Table 9

IDENTIFIED IN-PLACE U.S. COAL RESOURCES

Seam Thickness[a]	Coal Resources (billions of tons)		
	Measured	Indicated	Inferred
Less than 1000 ft overburden			
Thin	16	95	538
Intermediate	47	142	174
Thick	63	126	206
Subtotal	126	363	918
Greater than 1000 ft overburden		60	114
	126	423	1032
Total		1581	

SOURCES: Refs. 83 and 84.

[a]Thin, intermediate, and thick seam bituminous and anthracite coal, 14 to 28 inches, 28 to 42 inches, and more than 42 inches, respectively. Thin, intermediate, and thick seam subbituminous and lignite coal, 2.5 to 5 feet, 5 to 10 feet, and more than 10 feet, respectively.

base, has estimated that 433 billion tons of coal are amenable to mining, given current extraction techniques and economics (Table 10). However, only part of the 433 billion tons could be recovered because of the manner in which coal is typically extracted. Underground mining in the United States is normally accomplished using the room and pillar technique, in which pillars of coal are left in the mine to retard subsidence. As a consequence, only about 50 percent of the in-place coal is recovered. Longwall mining, not yet widely used in this country, in which controlled collapsing of the mine roof occurs, offers potential recovery rates as high as 80 to 90 percent. Surface mining is characterized by higher recovery rates, typically 80 to 90 percent of the coal in-place is recovered, except in extreme slopes. If the 50 percent recovery rate is applied to the underground-mineable reserves, and the 80 percent rate to the surface-mineable reserves noted in Table 10, the total economically recoverable reserves would amount to 257 billion tons, which is equivalent to about a 428 year reserve life

Table 10

MINEABLE IN-PLACE COAL RESERVE BASE OF THE UNITED STATES

Coal Type	In-Place Coal Reserves (billions of tons)			Estimated Heat Value (quadrillion Btu)
	Underground Mineable Reserves	Surface Mineable Reserves	Total	
Bituminous	192	41	233	6100
Subbituminous	98	67	165	2800
Lignite	--	28	28	400
Anthracite	7	--	7	200
Totals	297	136	433	9500

SOURCE: Ref. 69.

at current rates of coal production. This 257 billion tons of recoverable coal constitutes about 15 percent of the total identified in-place resources, and about 8 percent of the total resources. As mapping and exploration better define the substantial coal resources included in the inferred category of Table 9, and the extent of the hypothetical resources, the mineable coal resource base could expand appreciably.

United States coal resources underlie about 13 percent of the land area of the United States and are present in widely varying amounts in parts of 37 states. Figure 47 shows the major coal fields of the 48 contiguous states and the types of coals found in each region. An approximate distribution of coal resources by region is shown in Table 11. The eastern region of the United States, and primarily Appalachia, which has undergone intensive mining in the past, still has significant amounts of bituminous coal amenable to underground-mining techniques. The interior region, and most predominantly Illinois, has large deposits of both surface- and underground-mineable bituminous coal. The northern Great Plains states have vast deposits of both underground- and surface-mineable lignite in North Dakota and Montana. The Wyoming Powder River Basin has large deposits of surface-mineable subbituminous coal, with some seams 90 feet thick. Surface-mineable subbituminous coal deposits in the Rocky Mountain states are

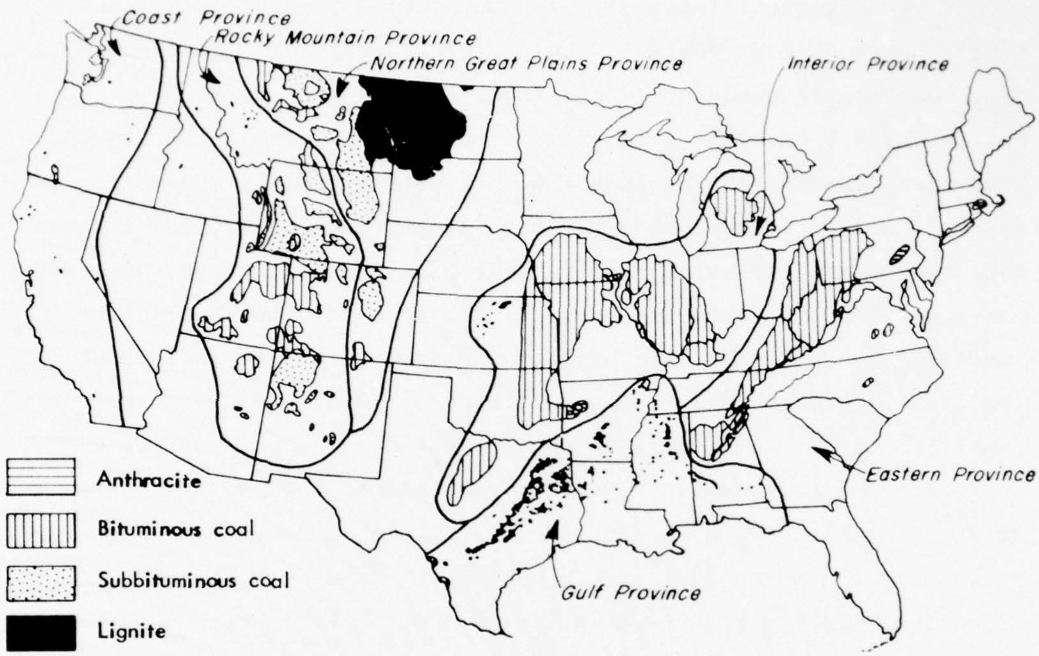

Fig. 47 — Distribution of U.S. coal resources (from Ref. 28)

Table 11

DISTRIBUTION OF U.S. COAL RESOURCES

Location	U.S. Coal Resources (billions of tons)		
	Identified	Hypothetical	Total
Eastern	276	45	321
Interior	277	259	536
Northern Great Plains	695	763	1458
Rocky Mountains	187	395	582
Other	146	181	327
Totals	1581	1643	3224

SOURCE: Ref. 28.

primarily located in northwestern New Mexico. Alaskan reserves of primarily subbituminous, and to a lesser extent bituminous coal, account for the bulk of the remaining reserves.(28)

There are significant differences in both the sulfur content and heat content of U.S. coals in the different regions. The subbituminous coal and lignite deposits in the Rocky Mountain and northern Great Plains regions have the great virtue of being low in sulfur content, with most deposits having less than a 1 percent sulfur content. Conversely, the bituminous coal deposits in the Appalachian and interior coal basins are characterized by their high sulfur content, with about one-quarter of the deposits containing from 1 to 3 percent sulfur.[84] The demands of the electric utility industry for these low sulfur western coals could directly conflict with the demands of a synthetic fuels industry for the more economic, surface-mineable western coals.

Although the western coals are generally low in sulfur, the lignite and subbituminous coal resources are also generally lower in heat content, which means that more coal must be transported and processed to deliver a given amount of energy than with the eastern and interior basin bituminous coals. Table 12 gives typical heat values for the different coals.

In summary, the domestic coal resource base is vast, and, as a consequence, has the potential for making a significant contribution to energy supplies in the future. The primary challenge, it seems, is to develop the coal resource base in an environmentally acceptable manner.

Table 12

HEAT VALUE OF U.S. COALS

Coal Type	Heat Value (Btu/lb)
Anthracite......	13540 - 14930
Bituminous......	12000 - 15630
Subbituminous...	8680 - 10760
Lignite.........	5900 - 7290

SOURCE: Ref. 83.

Oil-Shale Resource Base

Oil shale is a fine-grained sedimentary rock containing a solid organic material called kerogen. When oil-shale particles are heated, the organic matter is decomposed, forming oil vapors and gases. The oil vapors are condensed to form a syncrude product that may be refined into premium fuel products. Oil shale is usually found in layers or series of layers sandwiched between other layers of sedimentary rock.[28] The quality of the deposits is described by the average oil yield per ton of shale. Deposits yielding 30 or more gallons of oil per ton of shale are usually considered high grade; however, the characterization of the attractiveness or the economic recoverability of a particular deposit is very dependent on the technology available to extract the oil from the shale. The thickness of the shale deposit is another important factor in the determination of its recoverability. High-grade deposits are characterized by a thickness of at least 30 feet, with many high-grade deposits being over 100 feet thick.

About 90 percent of all the identified U.S. oil-shale resources are located in the Green River formation in western Colorado, Wyoming, and Utah, with most of the remaining resources located in the central and eastern United States (Fig. 48). Over three-quarters of the higher-grade deposits are in the Piceance Creek Basin northwest of Rifle, Colorado, between the Colorado and White Rivers.

A categorization of U.S. oil-shale resources according to their richness, location, and degree of uncertainty of the resource estimate is shown in Table 13. Given current technology and the uncertainties in future world oil prices, the only resources of immediate interest in Table 13 are the identified 25 to 100 gallon per ton deposits in the Green River formation. While these resources are currently classified as paramarginal because of the technological and economic uncertainties associated with oil-shale retorting processes, it is likely they would constitute the initial resource base for a synthetic fuels industry using oil shale.

Recovery rates for oil-shale deposits for underground and surface mining have been estimated to range from 40 to 65 percent.[28,86] If a 50 percent recovery factor is applied to the 418 billion barrel

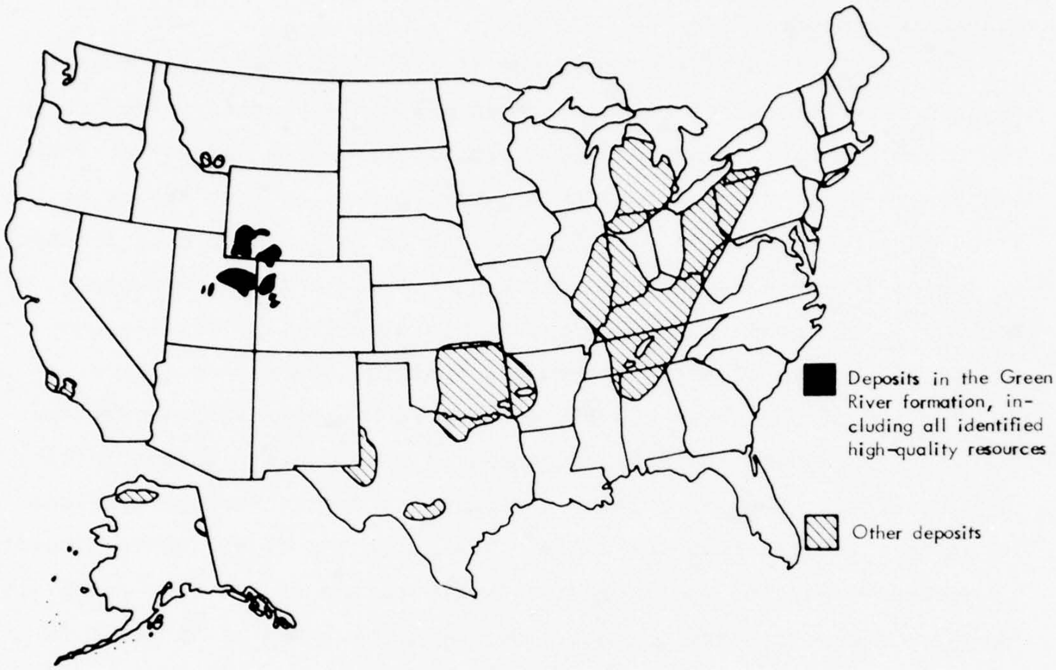

Fig. 48—Distribution of oil-shale resources (from Ref. 28)

estimate in Table 13, the recoverable oil-shale resources would amount to 209 billion barrels in the mined but unprocessed oil shale. This estimate can be compared with the 62 billion barrels of measured, indicated, and inferred recoverable U.S. crude-oil resources, and the estimated 50 to 127 billion barrels of additional remaining undiscovered crude-oil resources.(87) At a production rate equivalent to that of current domestic crude-oil production, the 209 billion barrels of oil shale might last about 69 years.

In situ recovery techniques, which might allow economical recovery of the lower-grade 10 to 25 gallons per ton shale in the Green River formation, could significantly enlarge the recoverable oil-shale resource base. In any case, the magnitude of the recoverable oil-shale resource base indicates that oil shale could potentially make a significant contribution to U.S. energy supplies, and particularly the liquid fuels supply, in the future.

Table 13

IN-PLACE U.S. OIL-SHALE RESOURCES

Location	Oil-Shale Resources (billions of bbl of oil)					
	Identified		Hypothetical		Speculative	
	25-100 Gallons per Ton	10-25 Gallons per Ton	25-100 Gallons per Ton	10-25 Gallons per Ton	25-100 Gallons per Ton	10-25 Gallons per Ton
Green River Formation (Colo., Wy., Utah)	418	1400	50	600	--	---
Chattanooga Shale equivalent formations (central and eastern United States)	--	200	--	800	--	---
Marine Shale (Alaska)	--	--	250	200	--	---
Other	--	--	--	--	600	23000
Totals	418	1600	300	1600	600	23000

SOURCE: Ref. 85.
NOTE: Blanks in columns indicate that only negligible quantities of oil-shale resources exist in these areas.

Bituminous Tar Sands Resource Base

Tar sands are a mixture of sand, water, and bitumen, a dense, usually black, hydrocarbon material, which is too viscous to be extracted by conventional petroleum recovery methods. Synthetic crude oil is currently being commercially produced from the vast Athabasca tar sand deposits in the province of Alberta, Canada.(88) It is estimated that about 895 billion barrels of proven in-place crude bitumen resources are located in Alberta.(89) In contrast, the United States is far less richly endowed with tar sand deposits. In-place tar sand deposits in Utah are estimated to contain about 28 billion barrels of bitumen, which account for over 95 percent of U.S. deposits.(19)

None of the Utah deposits are considered to be economically recoverable at present. The Department of the Interior has indicated that in 15 to 30 years it may be feasible to begin recovery of about

30 to 50 percent of U.S. tar sand resources, or about 9 to 15 billion barrels of oil. The Bureau of Mines, in a far more conservative estimate, considering shallow occurrences only, indicates that perhaps 2.5 to 5.5 billion barrels of oil from tar sands are recoverable.[20] Measured against the vast U.S. resource base of oil shale, coal, and even crude oil, and the time frame in which U.S. tar sands might be developed, it seems unlikely that U.S. tar sands will ever be a large-scale U.S. energy source.

CARBONACEOUS RENEWABLE RESOURCES

While the time span over which organic matter is converted into crude oil, natural gas, coal, etc., is measured in millions of years, energy can be retrieved from organic matter stored in green plants and other sources on essentially a continuing and renewable basis. This organic material can be obtained from the waste material that is a by-product of society's production and consumption of goods or from so-called "energy crops" grown specifically for energy production.

Organic waste material includes manure from livestock, plant residue left in the fields after normal harvest of agricultural products, industrial wastes from vegetable and meat processing and sawmills, logging wastes in the form of branches and deadwood left in the forest after saw timber has been removed, urban refuse, and municipal sewage solids. It has been estimated that in 1971 about 880 million tons of dry organic wastes were generated, perhaps 136 million tons of which might have been readily collectible.[90]

The energy content of the 136 million tons of wastes would be equivalent to roughly only 2 percent of U.S. energy consumption in 1971. As a consequence, it seems highly unlikely that organic waste products will ever be a significant energy source for a large synthetic fuels industry. However, the conversion of these wastes to energy has proved to be an attractive way to ameliorate some waste disposal problems, while at the same time supplementing energy supplies in selected regional applications.

The United States has large areas of arable land that are not cultivated, perhaps as much as 100 million acres of fallow crop land and

490 million acres of grassy pasture land.[91] If, to use a hypothetical and perhaps extremely optimistic example, a crop such as corn (maize) yielding 5 dry weight tons per acre per year with a heat content of 7200 Btu per pound were cultivated on all this land, the resulting energy would be about 42 quadrillion Btu, or about 58 percent of U.S. energy consumption in 1974. Clearly, it is extremely unrealistic to assume that all the acreage could be planted; nevertheless, the potential energy contribution from energy crops is large. Technological and economic uncertainties will have to be resolved before the potential of energy crops can be accurately assessed.

NONCARBONACEOUS, NONRENEWABLE ENERGY RESOURCES

Geothermal Energy

When the normally diffuse heat of the earth is concentrated due to local geologic conditions, these local reservoirs of thermal energy can be exploited as a source of energy. The only major commercial exploitation of geothermal steam in the United States to generate electricity thus far is of The Geysers, north of San Francisco.

Geothermal resources are usually grouped into three categories: (1) hydrothermal, (2) geopressurized, and (3) dry hot rock. Hydrothermal reservoirs consist of a heat source (magma) overlain by a permeable formation (aquifer) through which ground water circulates. The aquifer is capped by an impermeable foundation that prevents water loss. The energy can be recovered by drilling a well to transport the water and steam to the surface. Hydrothermal reservoirs are defined according to whether hot water or vapor dominates the reservoir, with vapor dominated reservoirs being the most commercially attractive but also the least common.

In geopressurized reservoirs the source of heat is not magma but rather clays in a rapid subsiding basin area, which trap heat in water-bearing formations. Dry hot rock formations are characterized, as the name implies, by the lack of a permeable aquifer. As a consequence, to recover the heat energy, the rock must be fractured and water injected.

Most of the major hydrothermal reservoirs are located in the western United States. About one-third of the known geothermal resource areas are in California. The geopressurized regions are concentrated along the Texas and Louisiana Gulf Coast.[28]

Geothermal resource estimates vary widely both in categorization and magnitude. A 1972 USGS document[92] indicates that about 10 quadrillion Btu of energy is available at the wellhead in identified recoverable reserves, and about 600 quadrillion Btu in paramarginal hot water systems. Another estimate[93] indicates about 540 quadrillion Btu at the wellhead of known reserves, with 18,000 quadrillion Btu of probable reserves, and 1.3 million quadrillion Btu of undiscovered reserves. These estimates should be tempered by the realization that characteristically only about 14 percent of the energy at the wellhead can be recovered in the form of electricity using current technology. Nevertheless, when compared with a total U.S. energy consumption of 73 quadrillion Btu in 1974, the resource base is definitely sizable. Given this resource base and the proper economic and technological climate, geothermal energy has the potential for making a meaningful contribution to the electrical generating capacity in the western United States by the turn of the century.

Nuclear Fission

When certain heavy atoms are bombarded with low-energy neutrons, they will split or fission, the products of the reaction being dissimilar atoms, neutrons, and an enormous release of heat energy. The neutron products can then react with other heavy atoms to repeat the reaction, the successive repetition of this process being termed a chain reaction. Such an uncontrolled chain reaction utilizing the heavy isotope uranium-235 was the basis for the first atomic bombs. When the chain reaction proceeds in a controlled manner, such as is the case in today's commercial nuclear reactors, the heat released in the reaction may be used in the generation of electricity, or as a source of process heat.

Of the several hundred naturally occurring atomic isotopes, uranium-235 is the only one that is spontaneously fissionable by the

capture of slow or thermal neutrons. Accordingly, the initial fuel for all energy conversion systems based on the fission reaction is uranium-235. The element uranium exists as three naturally occurring isotopes in the following proportions: 99.28 percent U-238, 0.71 percent U-235, and a trace (less than 0.01 percent) of U-234. Most of the uranium mined in the United States exists as uranium oxide, commonly termed yellowcake. This stable oxide of uranium is commonly used as the yardstick by which quantitative measurements of uranium reserves are estimated. For every ton of uranium ore mined, perhaps 4 to 5 pounds of uranium oxide can be extracted, from which 0.024 to 0.03 pounds of U-235 can be obtained.[28]

Table 14 indicates U.S. uranium oxide resources by cost and exploration status as determined by the Preliminary National Uranium Resource Evaluation program. Over 84 percent of the proven reserves are located in New Mexico and Wyoming.[28] The present uncertainty in uranium resource estimates has stimulated two major government uranium resource evaluation programs, one sponsored by ERDA, the other sponsored by the USGS.[94] The outcome of these resource evaluation programs may have a major impact on the planned expansion of the nuclear industry in the United States in the future.

Of course, estimates of uranium oxide resources have little meaning in an energy assessment unless the energy potentially and practically releasable in the uranium oxide is known. The energy content realizable from uranium oxide is very dependent on the technology used to effect the energy release. Today, commercial nuclear power plants use light-water reactors that consume uranium-235 as fuel. The amount of energy that can be released using this light-water reactor technology is the subject of considerable debate, with estimates varying by factors of seven or more.[94] ERDA, in its "National Plan for Energy Research, Development, & Demonstration," estimates that each short ton of uranium oxide can be converted to about 500 billion Btu of thermal energy when light-water reactor technology is utilized, assuming recovery and recycling of fissionable plutonium and uranium from spent reactor fuel produced by the fission reaction, and an assay of 0.2 percent of the unrecovered uranium-235 isotope in the fuel enrichment process. Using this value, the identified and potential uranium

Table 14

PROJECTED U.S. URANIUM RESERVES AND RESOURCES[a]

Index Cost[b] ($/short ton uranium oxide)	Uranium Oxide Resources (thousands of short tons as of 9/74)		
	Identified[c]	Potential (Undiscovered)[d]	Total
8	280	540	820
8-15	240	1010	1250
15-30	180	1200	1380
	700	2750	3450

SOURCE: Personal communication with ERDA-Germantown personnel, summer 1975.

[a]Does not include possible concentrations in Chattanooga shales, depleted uranium tails, or by-products of copper ore leach solutions, phosphoric acid production, or coal gasification.

[b]Does not include profit, interest on capital, or other ownership costs. Does not necessarily represent open-market prices.

[c]Includes measured, indicated, and inferred resources. Eight dollars/short ton identified reserves are reported to be economical in 1974. Eight to thirty dollars/short ton resource are reportedly not yet economical.

[d]Includes probable, possible, and speculative resources.

oxide energy resources noted in Table 14 would represent about 1725 quadrillion Btu, or about 60 percent more energy than the upper bound estimate of identified and undiscovered recoverable U.S. crude-oil resources. Using the most conservative estimate results in a uranium oxide resource base containing about 334 quadrillion Btu of energy, assuming no spent reactor fuel recycling, as is the case today, and a 0.3 percent tails assay.

It is difficult to draw any firm conclusions about the potential contribution of uranium resources to the U.S. energy supply in the future, given the uncertainty that exists in uranium resource estimates, in estimates of the energy recoverable from those resources using current reactor technology, and indeed, the rate at which nuclear reactors will be built in the United States. Perhaps the only conclusion that

can be made is that while the potential contribution of uranium to U.S. energy supplies is sizable, it is by no means inexhaustible when that energy is delivered using current reactor technology.

NONCARBONACEOUS, RENEWABLE ENERGY RESOURCES

Nuclear Fission (Breeder Reactors)

The potential energy content of the uranium oxide resource base changes dramatically if new breeder reactor technology is assumed to be available. Breeder reactors have the capability of converting abundant U-238 (the fertile, nonfissionable isotope) into fissile (fissionable) plutonium-239 and uranium-233, and thereby producing more fissionable fuel than they consume. This has the dramatic effect of making fertile uranium-238, the isotope which accounts for 99.28 percent of naturally occurring uranium, potentially available as an energy source, in contrast to the 0.71 percent of naturally occurring fissionable uranium-235, which can produce energy in light-water reactors.

If all the fertile natural uranium could be fissioned using breeder reactor technology, theoretically about 140 times more energy would be potentially available than with conventional light-water reactor technology, or about 70,000 billion Btu of energy per ton of uranium oxide. ERDA's current estimate is that breeder reactors might deliver about 36,000 billion Btu of thermal energy per ton of uranium oxide, or about 72 times the energy release using light-water reactors.(17) Hence, using breeder reactor technology, the identified and potential undiscovered uranium oxide resources noted in Table 14 would represent about 125,000 quadrillion Btu, or nearly 1700 times current annual U.S. energy consumption of all resources. Hence, the successful introduction of breeder reactor technology could turn uranium into a virtually inexhaustible domestic energy resource.

Nuclear Fusion

The atomic fusion of two or more of the isotopes of hydrogen, known commonly as hydrogen, deuterium, and tritium, results in the formation of helium, the next higher element on the atomic scale, and

an enormous release of energy. Such reactions are responsible for the huge quantities of energy radiated from our sun and the stars. The fusion of deuterium and tritium into helium in an uncontrolled manner is the basis for the so-called hydrogen or thermonuclear bomb. Research is under way to develop the technology to harness the energy released by a controlled fusion reaction to provide a useful source of energy for the future.

While the status of this technology area at present suggests that it is unlikely that nuclear fusion will make any significant contribution to U.S. energy supplies during this century, the interest in fusion is understandable when one examines the magnitude of total energy potentially available. In the case of deuterium fusion, the potential energy content of the deuterium in the world's oceans is about 40 billion times the annual U.S. energy consumption.[4] The available energy derivable from the lithium-deuterium fusion reaction is more limited by the availability of lithium, but still dwarfs other energy resources.

Solar Energy

The solar radiation falling on the earth's surface could conceivably meet a major portion of long-term U.S. energy needs on a continuing basis. It has been estimated that the solar energy falling on the 48 contiguous states is roughly 600 times current U.S. energy consumption.[95] However, the characteristically low energy value of the solar flux and its intermittent nature pose significant collection and energy storage problems.

Some water and space heating systems utilizing solar energy have already been commercially introduced in the United States, one of the primary remaining obstacles to their widespread introduction being the high initial capital costs for collector and storage systems. R&D on electricity generation using photovoltaic cells is centering on cost reduction. Significant contributions from this energy source will probably require reductions in costs of a factor of 100 or more.[96] Solar thermal electric power systems perhaps offer more promise, although proponents expect no major market penetration any earlier than the late 1980s at best.[97,98]

It is difficult to assess the ultimate contribution of other solar energy systems, such as wind generators, tidal power, ocean thermal gradient plants, etc. Their initial contributions will probably be regional in nature at the most favorable locations.

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